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# THE AUDIOMETRIC TESTING OF CHILDREN IN SCHOOLS AND KINDERGARTENS*

R. H. Farrant

* This is Report CAL 14 from the Commonwealth Acoustic Laboratories, Commonwealth Department of Health, Sydney, Australia, N. E. Murray, Director. Because of the wide interest in screening audiometry evidenced today, and because of the limited distribution of this excellent report on the topic by Dr. Farrant, the Editors offer this reprint as a public service. It is hoped that it will be found useful for the forthcoming national Conference on Screening Audiometry sponsored by the U.S. Department of Health Education and Welfare Childrens Bureau, the Maryland Dept. of Health, and the American Speech and Hearing Association.

## INTRODUCTION

In accord with one of their functions in aiding in the prevention of deafness, the Commonwealth Acoustic Laboratories have since their inception been concerned to assist the various school medical services in Australia in their efforts to improve methods and facilities for testing the hearing of children in schools and kindergartens.

The experience in 1948 of the Director of the Laboratories, Mr. N. E. Murray, in advising Dr. A. E. Machin, the then Director of the New South Wales School Medical Service, on the use of the Western Electric Type 4C group gramaphone audiometer using 'fading numbers' and group pure tone audiometry had convinced him that such group methods of testing hearing suffered from at least four serious drawbacks:

1. The apparatus was cumbersome to transport and set up
2. Such methods required for their use with groups of children a special fully sized class room with an unusually low ambient noise level
3. When attempts were made to measure the hearing of school children by the group methods, a considerable proportion of the younger children had difficulty in following instructions, and the method could not be used at all in the preliterate classes
4. Even when a group of school children had been tested by the group methods in a relatively short time per head, much time had to be spent in scoring and interpreting each individual test result paper.

Mr. Murray therefore turned to consider the possibility of designing and using small portable battery operated pure tone audiometers in screen testing the hearing of children individually in schools. Mrs. J. Wark, the first psychologist to join the staff of the Laboratories, had already shown (18, p. 4–6) that the hearing of children at least as young as four years of age could be accurately tested by pure tone audiometry with little additional equipment, and a simplification of the method for most children of school age seemed practicable.

By March, 1950 the Laboratories' acoustical and engineering technical staff had designed and produced a small portable battery operated pure tone audiometer (Type C.A.L. 1B) capable of tonal frequencies of 250, 500, 1000, 1500, 2000, 3000, 4000, and 6000, cycles per second and a decibel in-

tensity range of 90 decibels sensation level above normal thresholds (American Medical Association and Australian standards) and 10 db below.

Because Mr. Murray considered that screening could be restricted to 500 and 4000 cycles ('restricted frequency screening' which was much later advocated in the U.S.A.) an additional position for 500 cycles on the frequency switch was made near the 4000 cycles position to enable quick changes between these two frequencies.

A number of these audiometers were sent on loan to various school medical services. However, it soon appeared from inquiries and diverse reports that more knowledge and guidance was needed about the best methods of using these audiometers for screen testing the hearing of children in schools. Some school medical services were using them merely as clinical or screening audiometers in clinics on children already believed to have hearing loss. Other school medical services, while using the audiometers for screening purposes, did not seem to be adopting optimal methods in their use.

In view of this and the fact that there was little literature available on the use of this type of method* despite Watson and Tolan's excellent summary of other school hearing tests (23, Ch. 12, pp. 231–267), it was decided that the Laboratories should, if practicable, carry out a field study to ascertain the best methods and efficiency of using the type C.A.L. 1 B portable audiometers in the screen testing of the hearing of children in the schools. Most school medical services in Australia are operated by the local State Departments of Health but the Commonwealth Department of Health (of which the Acoustic Laboratories are a division) operates the medical services in schools in the Australian Federal Capital Territory. Therefore, departmental approval was obtained for the Laboratories to carry out, in cooperation with Dr. Edith Clement, the Department's School Medical Officer in Canberra, a field study of methods of using the type C.A.L. 1B portable battery audiometer in screen testing the hearing of children in Canberra, A.C.T., beginning early in the school year in 1951.

## METHODS AND PROCEDURES OF AUDIOMETRIC SCREENING IN SCHOOL AND KINDERGARTENS

### Aims and Criteria of Methods of Ascertaining Hearing of School Children

The major purposes of ascertaining the hearing of school children in schools and kindergartens are:

*Mrs. Dahl's book 'Public School Audiometry in Principles and Methods (3) was not then to hand and, in any case, dealt primarily with conditions in the U.S.A. and on a survey rather than experimental basis.

1. To enable early diagnosis and medical treatment with a view to eliminating, reducing or preventing the increase of any hearing losses

2. To enable early application of a hearing aid, if necessary, and appropriate parental guidance and educational guidance and placement or special supplementary teaching.

Granted the need for early ascertainment of hearing losses, what are the criteris desired of methods for ascertaining hearing losses of children in kindergartens and schools?

1. An ideal method for ascertaining hearing losses in children in kindergartens and schools should be of as high validity as possible.

2. An ideal method should preferably be economical in respect to apparatus, staff and time required for its application.

3. An ideal method of ascertaining hearing losses in children in kindergartens snd schools should preferably cause as little interruption as possible to general school routine and the class activities of the children.

4. An ideal method should be within the capacity of young children, and preferably interesting and not unduly disturbing for them.

We can now consider the various previous methods of ascertaining hearing losses in school children and to what extent they met these criteria for an ideal screening method, validity being the prime consideration.

## Earlier Methods of Ascertaining Hearing Losses of School Children

Ascertainment of hearing losses in children by their parents has long been known to be of low validity by the frequent discovery in schools and clinics of hearing losses in children unsuspected by their parents. However, this matter was recently formally studied by Kodman, Schweck et al (14), who compared the replies of parents and teachers to questions about the hearing of their children with the results of pure tone audiometry on those children. The major findings of this study were:

1. Parents and teachers did better than chance in detecting mild-to-moderate hearing loss pupils when only their successes were considered.

2. However, parents and teachers were both ineffective (teachers being perhaps slightly poorer) in identifying the normal hearing child and the hearing loss child. Both parents and teachers made incorrect judgments over 40% of the time. Pure tone audiometry was far superior to either the parents or the teachers.

Other experimental field studies by Curry (2) and Geyer and Yankauer (7) also confirm that teachers are very poor judges of the hearing acuity of their pupils as compared with audiometry, although they can make somewhat better chance identification of children with hearing losses, whether mild or substantial.

Ascertainment of hearing losses in children in schools by watch-tick, whisper and tuning forks was traditionally carried out by school medical services as a screen test of hearing. The development and application of one form or another of mechanical and later electro-acoustic audiometry has increasingly superseded the older methods because of much greater

validity and probably lesser requirement of specific clinical skills by the tester. However, at the time of these surveys, watch-tick, whisper and fork tests were in use by several school medical services in Australia.

Ascertainment of hearing losses of children in schools by recorded group speech audiometry began in the United States of America in 1926 with the introduction of the Western Electric A.A. type Phonographic Fading Numbers Audiometer (Watson and Tolan, 23, pp. 23-242). While such Phonographic Fading Numbers Audiometry constituted a big advance over the used live voice and whisper as screening tests of the hearing of children and were extensively used in schools in the U.S.A. (although not in Australia) until about the end of the second World Wsr, various studies such as those by Silverman (2) and West (24) showed it to be of rather low reliability and even lower validity (i.e., correlation with more accurate indicators of hearing losses such as pure tone audiometry). Moreover, our Laboratories' experience with the Phonographic Fading Numbers Group Audiometer in conjunction with the New South Wales School Medical Service indicated that it was even of lower practicability than some form of individual pure tone audiometry.

Whilst the substitution of more representative words than the numbers in group gramaphone audiometers somewhat improved their validity, particularly in not failing too often to screen out high tone hearing losses (Watson and Tolan, 23, pp. 243-252), group speech audiometry still had the following defects as compared with forms of individual pure tone audiometry:

1. Group speech audiometry (especially fading numbers) is of lower reliability and validity than individual pure tone audiometry, especially in identifying high frequency (tone) hearing losses (see West, 24, and Watson and Tolan 23).
2. Group speech audiometry is practicable only with literate children.
3. Group speech audiometry requires a classroom which must be of considerable size and provide fairly quiet conditions.
4. Group speech audiometry ewuipment is bulky and heavy to transfer.
5. Group speech audiometry requires two persons to administer it.
6. Pupils answer sheets obtained from group speech audiometry require marking and also careful interpretation after completion of the testing.

Ascertainment of hearing losses of children in schools by group pure one audiometry therefore tended to be the next stage in the evolution of methods of screen testing hearing. However, as most of the disadvantages of group speech audiometry - especially (2) to (5) - also pertained to group pure tone audiometry and as a similar necessity to mark and interpret answer sheets subsequent to the actual group testing reduced the seemingly high speed of screen testing, one form or another of individual pure tone audiometry was soon tried in American schools at least. Thus Newhart's study in Minnespolis public schools in 1940 (reported by Watson and Tolan, 23, p. 234) was one of the pioneering applications of pure tone audiometry in the screen testing of hearing of children in schools.

However, it was about another ten years before the application of individual pure tone audiometry in screen testing hearing of children in Australian schools came about.

## THE C.A.L. BATTERY-OPERATED SCREENING AUDIOMETER TYPE B.1

The C.A.L. Screening Audiometer Type B.1 was designed by these Laboratories to conform to the American Standard Specifications for Audiometers for General Diagnostic Purposes, with the exception that masking and bone conduction devices are not provided. It is easily portable being contained in a case, the dimensions of which are 3 7/8" x 9 1/4" x 7 3/8" and is completely battery operated. All controls are mounted on a panel 3 7/8" wide and 9 1/4" long, and are enclosed by a removable cover. Access to the batteries is provided by a similar cover at the rear of the instrument.

The list tones are generated by a resistance-capacity controlled oscillator, with set frequencies of 250, 500, 1000, 1500, 2000, 3000, 4000 and 6000 cps which may be selected separately by a switch on the control panel. The signal from the oscillator is amplified sufficiently to drive a Permoflux PDR10 earphone fitted with a MX41/AR cushion to give the correct acoustic pressures in an American National Bureau of Standards 9A coupler. The hearing loss control varies the gain of this amplifier, and therefore the acoustic output of the earphone. The control is calibrated in 5 decibels steps over a range of 100 decibels, i.e., from 90 decibels to −10 decibels hearing loss. A switch is provided to interrupt the tone without producing audible transients and to give the correct tone rise and decay times specified in the American Standard. The 1500 signal is metered and may be adjusted to a predetermined level by means of calibration control. This ensures that an accurate calibration is maintained at all times. Both the low and high tension battery supplied are also metered. Sub-miniature valves are used throughout.

## SPECIFIC PURPOSE OF THE C.A.L. STUDIES

The main general purpose of hearing screening surveys and experiments in Canberra schools was to ascertain the best methods of using the C.A.L. portable battery-operated audiometers in screen testing the hearing of children in schools and kindergartens.

Detailed purposes of our studies were specified as follows:

1. To ascertain suitable methods of assembling pupils for screen testing of their hearing.
2. To ascertain the best procedures and techniques of screen testing hearing of children in schools and kindergartens.
3. To ascertain at which audiometric frequencies it is necessary to screen test children's hearing.
4. To ascertain what audiometric intensities it is desirable to use in such audiometric screening.

5. To discover what rates of testing children are practicable with such individual audiometric screening methods.

6. To discover the incidence of hearing defects in kindergarten and school children (in the Canberra area at least).

7. To discover the types and aetiology of hearing defects in such kindergarten and school children.

8. To ascertain appropriate methods for medical and educational treatment and follow-up of cases ascertained to have hearing loss.

Our experience shows that desirable criteria in the choice of rooms for audiometric screening in schools and kindergartens are as follows:

1. Preferably use the school medical examination room if one has been allocated for this purpose and other conditions are satisfactory.

The importance of designing school buildings to include a medical examination room that will provide conditions, particularly quiet conditions, suitable for use in audiometric screening, as well as for other purposes, is explained by our experience and particularly the subsequent experience of Dr. Clement.

2. The room for audiometric screening should provide moderately low ambient noise levels. Such ambient noise levels need not of course be as low as those required for clinical purposes in audiometric threshold testing. We did not measure ambient noise levels in rooms used during our screening surveys but merely judged whether they were low enough for screening purposes by ear and by degree of difficulty experienced in screening.

3. The room for audiometric screening and approaches to it should preferably have carpet or rubber floor covering to reduce noise created by the children walking or shuffling their feet.

4. The room for audiometric screening should be located reasonably close to the classes from which children are being screened.

5. The room for audiometric screening should be furnished with a table and form or chairs of suitable height for the children (small ones are necessary for kindergarten children) and a chair appropriate for the tester.

## Methods of Mustering Children for Screening and Returning them to Class.

Various methods of mustering children for test and returning them to class were tried, particularly where conditions varied such as ages of children, distance of test room from class rooms, etc. However, the method that was generally most efficient in school was as follows:

1. After contacting the principal and teacher concerned, usually I, as tester, conducted an initial batch of about five children to the test room. When larger groups of children were tried, those waiting long tended to get bored and noisy.

2. The children were seated on a form opposite the tester and advised of the purpose of the test, a volunteer for test accepted and testing begun.

3. After three children had been tested, they were instructed to return to class and ask the teacher to send another batch of five children for testing. The remaining two children, or sometimes a single child, needing a full audiogram was tested while the next group was coming.

4. In the case of younger school children the principal or teacher usually designated a messenger or runner to contact the classes and conduct the batches of children to and fro.

We subsequently learned that Dahl (3, pp. 218-220) had arrived independently at the same procedure for desirable frequency audiometer testing-showing how it contributes to what West calls "despatch" in the introduction to the book.

In kindergartens, procedure was similar, except that each batch of five children was brought by a teacher who was familiar with the children snd so able to reassure them, if necessary, and make clear what their names were. The ancillary assistance of teachers to facilitate testing in kindergartens was necessary also to locate and conduct the children who were, of course not rigidly grouped in classes but mainly circulating between variously located play and task situations.

## General Methods of Screening with the C.A.L. Individual Pure Tone Audiometer

The methods finally adopted were adapted from the methods used in clinical audiometry in our laboratories with considerable modifications to meet the screening situation. Usually, less elaborate screening methods were needed for children in schools than for those in pre-school kindergartens.

### Method of Screen Testing in Schools

1. Before beginning each screening session, the C.A.L. battery-operated audiometer was given the routine electrical calibration check and adjustment and, when the rare necessity occured, one or both batteries were replaced.

2. A new record form Cal.9 was taken and headings filled in appropriately with special note made of the time of beginning testing.

3. When the group of about five children arrived, they were welcomed in a friendly fashion, and directed to sit on the form or chairs on the other side of the table from the tester.

4. The tester briefly advised the group of children of the purpose of the test and instructed them to say "yes" whenever they heard the audiometer "whistle", giving a quick, dramatised, demonstration while applying the earphone to his own ear.

5. The children were asked who would like to be first to be tested. A volunteer was accepted, or if no one volunteered, a child who appeared reasonably confident was chosen as if it were a privilege. Then the other children were given leadership, undue anxieties avoided, and refusals almost entirely obviated.

6. The audiometer earphone was placed on the ear of the first child who then held it on and the tester released a spurt of tone of 4,000 c.p.s. sensation level 15 db for a duration of about one second. (4,000 c.p.s. was adopted as the initial testing frequency rather than 500 c.p.s. regardless of whether testing was done at additional frequencies or not because both experience and experimental investigation showed 4,000 c.p.s. to be more quickly recognized by children as distinct from any ambient noise present.

7. a. If the child responded unequicovally to a spurt of tone at 15 db above normal threshold at 4,000 c.p.s.:

Once he clearly understood the instructions, screen testing was similarly carried out at the other test frequency (usually 500 c.p.s.) or frequencies, and then the other ear was tested similarly.

b. If the child did not respond correctly to spurts of tone at 15 db above normal threshold at each of the test frequencies used on each ear:

A full air conduction audiogram of the failing ear (or ears) was taken using the descending technique, S's name snd thresholds being recorded appropriately in the upper part of Form Cal. 9.

8. Then the next child was tested, no further instruction being needed, except perhaps regarding the careful placing of the earphone on the ear.

9. After about three or four children of the group had been tested, they were

instructed to return quietly to class and ask the teacher to send the next group of five.

## Frequencies and Intensities Required in Audiometric Screening

As shown in the first section of this Chapter, the principal aim in audiometric screening is to try to identify with minimum effort each child with hearing losses of any significance for communication or pathology. Therefore in screening audiometry, each child is tested initially merely to ascertain if it can hear (or more correctly, respond to) tones at certain critical frequencies and of certain critical intensities, and the more time-consuming test of taking a full threshold audiogram is avoided, except with children failing the screen test. Moreover, some compromise must be made between the audiometric intensities desirable in screening and those possible under the ambient noise levels occurring where screening in schools takes place. The question is what are the audiometric frequencies and intensities that meet these conditions for screening.

Regarding the audiometric frequencies required, the most common technique used in pure tone audiometric screening in the U.S.A. at the time, was the "sweep-frequency technique" in which screening was carried out at 15 db above sound threshold (A.M.A. Standards) over the usual clinical audiometer frequency range, i.e., from 250 c.p.s. to 4,000 c.p.s. or even 8,000 c.p.s. (see Wallace, 22) and Dahl (3, p. 149). However, we believed on the following grounds that it was unnecessary to screen test at all of these frequencies:

1. Beasley (1) had shown that correlation between hearing losses by air conduction is extremely high and regression linear for the four tones, 64, 128, 256 and 512 c.p.s.

2. His studies and our own extensive clinical experience had shown that in cases where hearing losses occurred at any of the higher frequencies, they virtually always involved hearing losses at 4,000 c.p.s. Indeed, even high frequency "notching losses" due to acoustic trauma manifested themselves most markedly at 4,000 c.p.s.

3. Our own clinical experience and the literature indicated that U-shaped hearing losses, in which hearing is virtually normal at 500 c.p.s. and 4,000 c.p.s. with significant losses in the intermediate frequencies are extremely rare.

We therefore considered it necessary to screen merely at frequencies of 500 c.p.s. and 4,000 c.p.s. Originally we were so convinced of this that in our first survey in 1951 we used only those two frequencies in initial screening. However, subsequently we considered it desirable to prove our contention in the field and our second study (reported in Chapter IIII) investigated this question in detail.

Regarding the audiometric intensities required, a pilot experiment at Telopea Park public School during our earlier study showed that sensation levels of 10 db at both 500 c.p.s. and 4,000 c.p.s. were inadequate, allowing only comparatively low rates of testing and being extremely difficult or impossible to use because of masking by ambient noise under some screening conditions encountered. It was shown that screening intensities

of 15 db at 4,000 cps and at 500 cps were practicable under most testing conditions, allowing rapid testing while detecting hearing losses of any communicative or pathological significance, although under the poorest testing conditions it proved desirable to resort to 20 db at 500 cps. However, whilst the C.A.L. screening audiometer used in the initial study (Type B1, No.9) was calibrated to within the standards of output for audiometers specified by the Council on Physical Medicine of the American Medical Association (which these Laboratories have adopted as Australian standards), it was subsequently found on technical grounds that our audiometer calibration required an increased output of 2.5 db st 500 cps to conform more closely to A.M.A. Standards. Our second major study reported in Chapter III investigated more extensively the relative merits of various screening intensities and frequencies, using C.A.L. Type B1 screening audiometers incorporating the required slight adjustment in output at 500 cps.

Incidentally our earlier pilot experiment indicated that there is some advantage in beginning screening at 4,000 cps rather than at 500 cps in that the 4,000 cps tone was more quickly and easily perceived and responded to by the testees (probably because of its greater contrast with the ambient noise spectrum usually present).

## Rates of Testing

Comparative rates of testing of children in the upper primary school grades using three different combinations of screening frequencies and intensities were investigated and are reported in the next chapter.

Rates of testing of children at different grade levels ranging from pre-school kindergarten through to the final year of secondary high school were extensively investigated in our first survey, using 15 db at 4,000 cps and mainly 20 db (equivalent to 17.5 db in the second study) at 500 cps. These rates of testing (including screening and full air conduction audiograms on cases failing the screening) are set out in the following table:

COMPARATIVE RATES OF TESTING OF CHILDREN IN VARIOUS EDUCATIONAL STAGES
Note: Testing here includes both screen tests and full air conduction audiograms on cases failing the screening

| Grades and Approx. Ages | Total School Working Days Testing | Total in Hrs+Min | No. | Rate per Working Day | Rate Per Hr |
|---|---|---|---|---|---|
| Pre-School (3–5 Yrs) | 3 1/3 | 9 5 | 136 | 40.8 | 15.0 |
| Primary (5–8 Yrs) | 5 1/5 | 21 15 | 774 | 148.8 | 36.4 |
| Primary Grades 9–12 Yrs) | 6 3/5 | 22 5 | 1051 | 159.2 | 47.6 |
| Secondary (13–17 Yrs) | 2 2/5 | 10 20 | 657 | 273.8 | 63.6 |
| Totals | 17 8/15 | 62 45 | 2618 | 149.3 | 37.0 |

The greater hourly rates of testing for the higher educational levels are statistically highly significant (far beyond the 0.1% probability level using Chi-square technique). This is undoubtedly due to the greater men-

tal age, skill and confidence of the older children which enables them to understand and respond quicker to the test and also to move in and out of the testing room faster. Comparison of these results with results for incidence of hearing defects (see Chapter IV) shows that differences in incidence (higher incidence requiring full tests and hence taking longer) have not importantly affected these findings on testing rates. For example, incidence of hearing defects found in pre-school and lower grades primary school children is less than that for higher grades primary school children, yet the testing rates are much slower.

These rates of testing show that this individual pure tone screen testing technique is superior to the group gramaphone speech audiometer even in enabling faster testing rates. Thus Watson and Tolan (23, p. 263) in their comprehensive account of school hearing tests and problems state that the audiometric manual of the Pennsylvania Department of Public Instruction allows from twenty minutes to half an hour to complete a group phonographic test on both ears, without counting the time necessary to set up and re-pack the equipment. The usual maximum number of sets of headphones used would not be more than 40 and the test is to complex to be valid below about the third grade primary school level. Thus, including time for setting up and administering the group speech gramaphone audiometer test, pupils above third primary school grade can be tested only at about a rate of 40 per hour (compared with 47.7 similar older primary school children per hour by our method).

Similarly our pure tone screen testing technique enables faster testing rates than even the group phonographic pure tone audiometer.

Our rates of testing can be compared favourably also with those obtained by Wallace (22, esp. p. 1), using a "sweep-threshold" technique in which children's hearing in each ear was tested at a standard screening level (15 db above normal threshold) at octaves from 8,000 to 250 cps. His pilot study of 453 high school students who had already been given full audiograms and were thus experienced in being audiometrically tested enabled a testing rate of 56.6 children per hour. Our comparable results for high school students (at Canberra High School) were 63.6 children per hour. Moreover, these children had not experienced pure tone audiometry before. However, Wallace's study gave results of a comparable order showing that even much more elaborate individual tone audiometric screening methods enable rapid rates of testing.

Regarding annual testing rates attainable, Wallace mentions that his experience shows that the average well-trained audiometrician should be able to screen test 30,000 to 40,000 school children per year using his individual pure-tone sweep-threshold screening technique, allowing for a 4½ hour school testing day. Combining our results on testing rates at the primary and secondary school levels (presumably giving a fairly typical weighting of the proportions of the school groups in the community in general), we find that primary and secondary school pupils were tested at the average rates of 46.2 children per actual testing hour and 174.8 children per

working day. Dividing the hourly testing rate into the rate attained per working day, we find that we, in effect, attained only 3.8 effective working hours per school day. This is lower that the 4½ hour school testing day estimated by Wallace and the approximately 5 hour average teaching school day. The disparity is probably due largely to the fact that this survey was not part of the regular school medical programme and extra time was required to make new arrangements for each section of each school, to find appropriate rooms for testing, etc. Even so, our average daily testing rate of approximately 175 children per day indicates that a trained audiometrist could test approximately 35,000 primary and secondary school children per school year (allowing about 43 school working weeks per year, 5 school days per week, and for public holidays). Regular arrangements as are possible for a school medical service might well enable a considerably higher total of school children per year to be tested.

The similar magnitude of Wallace's figures and ours on possible rates of testing indicates that our rates were not atypical of those attainable by a well-selected and trained audiometrist working under proper supervision and particularly with regular procedural arrangements as through a school medical service.

### Reporting of Cases Failing Tests

The primary purpose of audiometric screening and ascertainment of hearing losses in children is, of course, to help enable action to be taken to eliminate, reduce, or limit any hearing loss by medical treatment, if possible, and in cases where the hearing loss cannot be so eliminated, to enable action to be taken to reduce its effects, particularly on communication.

In our serveys we reported our findings on cases with hearing losses to the School Medical Officer (Dr. Clement), together with a copy for the teaching staffs with suitable interpretations and suggestions regarding desirable seating position in class, etc. Dr. Clement, and in our second survey, Dr. Khan, our laboratories part-time Ear, Nose and Throat Specialist, subsequently medically examined these children, who were found to have hearing losses. Later parents were appraised of the existence of any hearing losses and need for medical or other treatment of their children, and the detailed audiometric and medical data was available to any medical practitioner who inquired in the course of treating one of these cases.

## THE RELATIVE MERITS OF THREE SCREENING TECHNIQUES USING DIFFERENT FREQUENCIES AND INTENSITIES

### Introduction

Two basic questions in deciding how to carry out individual pure-tone audiometric screening to best effect are:

1. What are the essential frequencies at which screening should be carried out to ensure that all cases with hearing losses of communicative or pathological significance are discovered?

2. What are the intensity levels of the tones that should be used in screening sufficient to enable testing at reasonably fast rates to be done under the ambient noise levels encountered in places of testing in schools, yet not so high that cases with hearing losses of communicative or pathological significance are missed?

As discussed in Chapter II, we believed, on the basis of indirect evidence from the literature and our own clinical experience, that virtually all hearing losses of any significance could be discovered by screening at the frequencies of 4000 cps and 500 cps and that screening at the intermediate frequencies as in the usual overseas sweep screening technique was unnecessary. Also our pilot experiment in 1950 indicated that intensity levels of 15 db at 4000 cps and 15 or 20 db at 500 cps were optimal for screening in most schools and kindergartens. The pilot experiment also showed that it was better to begin screening at 4000 cps than at 500 cps.

To provide definite answers on these issues, we therefore conducted an extensive investigation into the relative merits of screening at the following three frequency-intensity combinations:

a. 15 db sensation level (A.M.A. audiometric standards) at frequencies of 4000, 2000, 1000 and 500 cps (presented in that order).

b. 15 db at 4000 and 500 cps.

c. 15 db at 4000 cps and 20 db at 500 cps.

## Specific Purposes, Design and Procedures of the Comparative Investigation

The major relevant specific purposes of this comparative investigation were:

1. To compare the efficiency of the three frequency-intensity screening combinations (or "techniques") in discovering hearing losses of school children, as shown in:

a. the comparative degrees and characteristics of hearing losses found. (It was especially desired to learn by screening a substantial sample of children at 15 db sensation level at 4000, 2000, 1000, and 500 cps whether cases occur with hearing losses of 15 db or more at 1000 or 2000 cps but with no loss or losses less than 15 db at 4000 and 500 cps);

b. the comparative incidence of hearing defects found by the three techniques (provided that the tone incidence of such defects in the school population could be experimentally 'controlled').

2. To compare the rates of testing attained with the above three frequency–intensity techniques; and

3. To compare the relative practicability of screening at each of the three frequency–intensity combinations under the various ambient noise conditions in the different places of testing used in some typical schools.

It was considered that the purpose No. 1a (see above) would require the screening of up to 1000 children as it was likely that if cases with hearing de–defects at only 1000 or 2000 cps existed at all, they would be of relatively very low incidence.

Regarding purposes Nos. 2 and 3 (see above), it was considered that only relatively small samples were required (about 150 children for each one of the two screening levels) because the Pilot Experiment on Screening Levels had already provided much suggestive data on this point and it was likely that the revised calibration of the audiometers increasing the output by 2.5 db at 500 cps would provide for satisfactory screening at the revised 15 db level at 500 cps.

The earlier survey had indicated that an average screening rate of about 150 primary school children per school working day might be expected (or slightly less perhaps since much of the screening would be done at four frequencies instead of two as previously).

It was decided to confine these investigations to primary school children, particularly above the infants grades, as the most representative of children to whom large scale screening would usually be applied.

Canberra schools, whose school medical services are under the control of the Commonwealth Department of Health, were again chosen.

It was considered wise to begin testing from Grade 3 upwards, using the four screening frequencies (purpose No. 1a on the first two days, then to spend about one and a half days using alternately the two screening levels at two frequencies only (purposes 2 and 3), and then to resume using the four screening frequencies on the highest primary grades children and also on Grade 2 and lower grade level children. Thus purpose 2 would be investigated after the audiometrists had overcome most of any initial practice effects (e.g., on rates of screening) and on children of middle grades level, and purpose No. 1a would be investigated in the earlier and the later parts of the study using children of both higher and lower grades.

The following experimental design was therefore adopted:

| SCREENING FREQUENCIES AND LEVELS | EXPERIMENTAL PURPOSE | WORKING DAY IN ORDER | GRADES | N |
|---|---|---|---|---|
| 4000, 2000, 1000 and 500 cps at 15 db above Normal Threshold | No. 2 | First<br>Second<br>Third (morn.) | 3<br>3 & 4<br>4 | 300<br>300<br>200 |
| 4000 cps at 15 db<br>500 cps at 15 Db | No. 1 | Third (aft.) | 4 & 5 | 100 |
| 4000 cps at 15 Db<br>500 cps at 20 Db | No. 1 | Fourth (morn.) | 5 | 200 |
| 4000 cps at 15 Db<br>500 cps at 15 Db | No. 1 | Fourth (aft.) | 5 & 6 | 100 |
| 4000, 2000, 1000 and 500 cps at 15 DB | No. 2 | Fifth | 6 & 2 | 300 |
| | SUMMARY | | | |
| 4000, 2000, 1000 and | No. 2 | | 3, parts of 4,6, & 2 | 1100 |
| 4000 cps at 15 Db | No. 1 | | Parts of 4 & 6 | 200 |
| 4000 cps at 15 DB<br>500 cps at 20 Db | No. 1 | | 5 | 200 |

While this design does not provide a logically perfect experimental means of testing purposes 2 or 1b of this investigation in that the practice effects on testing rates and the grade levels and incidences of hearing defects are not perfectly controlled, it is considered adequate for the purposes of the investigation to show up any differences of practical significance. Moreover, this experimental design constitutes about as adequate control as practicable in an essentially field investigation – a purely experimental investigation being impracticable and irrelevant.

In practice this experimental design was substantially adhered to with only very minor modifications necessitated by practical circumstances in the field.

Results of the investigation are described below:

The Comparative Efficiency of the Three Techniques in Discovering Losses

In this investigation we were mainly concerned with the degree, type and incidence of hearing defects (i.e., ears or children failing the relevant hearing tests) relative to each of the three frequency–intensity screening techniques, rather than overall incidence rates, a major concern of the previous survey.

a. Comparative Incidence of Defects found by the Three Techniques

The incidence of hearing defects for the three different screening techniques, with subsidiary statistics for schools (hence audiometrist) and with grand total is tabulated as follows:

INCIDENCE OF HEARING DEFECTS FOR THE THREE SCREENING TECHNIQUES

| School | Numbers Tested | Numbers Failing Screen Test | | | | Percentage Incidence | |
|---|---|---|---|---|---|---|---|
| | | One Ear | Both Ears | Total Children | Total Ears | Children | Ears |
| **Screening at 15 DB at 4000, 2000, 1000, and 500 cps** | | | | | | | |
| Ainslee | 451 | 33 | 12 | 45 | 57 | 10.0 | 6.3 |
| Telopea Park | 290 | 16 | 8 | 24 | 32 | 8.3 | 5.5 |
| Totals | 741 | 49 | 20 | 69 | 89 | 9.3 | 6.0 |
| **Screening at 15 Db at 4000 and 500 cps** | | | | | | | |
| Ainslee | 104 | 6 | 12 | 18 | 30 | 17.3 | 14.4 |
| Telopea Park | 118 | 4 | 6 | 10 | 16 | 8.5 | 6.8 |
| Totals | 222 | 10 | 18 | 28 | 46 | 12.6 | 10.4 |
| **Screening at 15 DB at 4000 cps and 20 Db at 500 cps** | | | | | | | |
| Ainslee | 100 | 4 | 1 | 5 | 6 | 5.0 | 3.0 |
| Telopea Park | 155 | 5 | 5 | 10 | 15 | 6.5 | 4.8 |
| Totals | 255 | 9 | 6 | 15 | 21 | 5.9 | 4.1 |
| **Grand Totals** | | | | | | | |
| | 1218 | 68 | 44 | 112 | 156 | 9.2 | 6.4 |

Note: The percentage incidence of ears failing the screening test is the most important parameter

It is obvious that these statistics on relative incidence of ears or cases failing the various screen tests tell us little about the relative efficacy of the screening techniques because the nature and incidence of hearing defects in the various samples tested are not controllable, e.g., R.W. testing at Ainslee Public School using the screening technique of 15 db at 4000 and 500 cps obtained the extraordinarily high incidence of 14.4% of ears tested failing the screen test, whereas R.H.F., testing at Telopea Park Public School on a school population of similar grades, ages, and probable socio-economic status, obtained an incidence of 6.8% of ears failing, giving a combined average of 10.4% of ears failing. Moreover, using the screening technique of 15 db at 4000, 2000, 1000, and 500 cps, which might be expected to obtain a somewhat higher or at least the same percentage incidence of ears failing since it involved screening at the same intensity lvel and at two intermediate frequencies, obtained a percentage incidence of only 6% of ears failing.

Clearly the relative efficacy of the various screening techniques for discovering minor hearing losses can be determined only by comparing the degree (especially the minimum degree) and characteristics (i.e., at which frequencies) of hearing losses found.

b. Comparative Degrees and Characteristics of Hearing Losses Found, Using the Three Screening Techniques

(1) General: The comparative data on the distributions of average hearing losses (calculated by the C.A.L. methods) of ears failing the various techniques is tabulated below:

DISTRIBUTIONS OF AVERAGE HEARING LOSSES FOUND BY THREE SCREENING TECHNIQUES

| Screening Technique | No. Ears Tested | No. Ears Failing | Range of Ave. Losses | 10th Cent | 20th Cent | Median (50th Centile (db) |
|---|---|---|---|---|---|---|
| 15 Db at 4000, 2000, 1000 and 500 cps | 1482 | 89 | 0–82 | 5.8 | 8 | 13 |
| 15 Db at 4000 and 500 cps | 444 | 46 | 3–79 | 6.3 | 10 | 15.5 |
| 15 Db at 4000, 20 Db at 500 cps | 510 | 21 | 4–61 | 8 | 9 | 15 |

This table indicates that the technique of screening at 15 db at 4000, 2000, 1000 and 500 cps tends to pick up somewhat smaller average hearing losses than the other two techniques. (Incidentally the ear with 0 db average loss had a 10 db loss at 4000 cps only, being better than normal at 2000 cps with –5 db.)

However, comparison of the minimal and median average hearing losses found by each of the three screening techniques is a rather crude and inadequate way of comparing their efficacy because the screening techniques differ in paetial but important respects other than intensity level, e.g., they all test at 15 db at 4000 cps.

The best way of comparing the efficacy of these screening techniques is to examine the full audiograms of ears failing each of the screening methods to discover whether the unique characteristics of each particular method are efficacious. For example, the first screening technique is unique in screening at two additional intermediate frequencies (1000 and 2000 cps), and the audiograms of ears found with hearing loss should be examined to lewn whether this method discovered hearing losses that would not have been discovered merely by screening at 4000 and 500 cps at 15 db. Similarly the third screening technique is unique in that it screens at intensity level 20 db, not 15 db, at 500 cps, and therefore we should examine the audiograms of resultant ears with hearing loss to discover whether the technique misses cases with losses at 500 cps which would be picked up by the other two methods

We inerefore examined the detailed audiograms of ear discovered with hearing losses by each of the three screening techniques in the light of the unique characteri stics of each screening method.

(2) Details of Hearing Losses Found, Using Technique of Screening at 15 Db at 4000, 2000, 1000, and 500 Cps

We examine details of audiograms of ears with hearing losses found using this screening method to discover whether ears occurred which failed the screen test at only 2000 or 1000 cps and so had hearing losses at 2000 and/or 1000 cps only, being within normal limits at 4000 and 500 cps.

Such defective ears would, of course, not be discovered using the second method which screened at 15 db at 4000 and 500 cps only.

Below are details of cases found with significant hearing losses (15 db or more) at 2000 and/or 1000 cps but with hearing within normal limits (10 db or less) at 4000 and 500 cps, using the method of screening at 15 db at 4000, 2000, 1000, and 500 cps:

CASES WITH SIGNIFICANT LOSSES AT 2000 AND/OR 1000 ONLY, USING FIRST SCREENING TECHNIQUE

| Child | Grade and Age | Date of Test | Ear | 250 | 500 | 1000 | 2000 | 4000 | Av. | Results of E.N.T. Exam 19/12/52 |
|---|---|---|---|---|---|---|---|---|---|---|
| C.J. | 3A 9 | 24.11.52 | R | 0 | −5 | 10 | 20 | 5 | 10 | Absent |
| M.L. | 3R 8 | 25.11.52 | L | −5 | 0 | 0 | 15 | 10 | 7 | T.M. normal, nose dry and clear. Tonsils negative. No glands. No medical action |
| D.B. | 4B 10 | 25.11.52 | R | | 0 | 5 | 15 | 10 | 5 | T.M. normal, nose dry and clear. Tonsils negative. No medical action required |
| B.M. | 3W | 25.11.52 | R<br>L | 0 | 0 | 5<br>0 | 15 | 0 | 7 | Absent |
| B.M. (Later retest | | 28.11.52 | R<br>L | — | 5 | 10<br>−5 | 20 | 0 | 11 | |

The above table shows that four ears were found with hearing loss at 2000 and/or 1000 cps only out of a total of 89 ears discovered with hearing losses, using the method of screening at 15 db at 4000, 2000, 1000 and 500 cps.

Thus ears with hearing losses at 2000 and/or 1000 cps occurred in four out of 89 or 4.5% of ears found with hearing loss or 0.3% of all ears screen tested, using the first screening technique.

Although the incidence of approximately 0.3% of ears having losses at 2000 and/or 1000 cps out of all ears is minute, the incidence of 4.5% of such ears relative to the number of defective ears found warrants consideration because the main object of screening audiometry is to discover ears with defective hearing, especially those requiring medical or prosthetic treatment, rather than simply to verify that most ears have normal hearing.

The practical significance of this is whether ears with significant defects in thresholds at 2000 and 1000 cps only occur with such frequency and degree of hearing loss and require medical or prosthetic treatment that it is in practical screening necessary to spend the additional time required to screen all ears at 2000 and 1000 as well as 4000 and 500.

As stated, the small but significant percentage occurrence warrants consideration.

Regarding the importance of the degree of the hearing losses for communication, none of the four cases tabulated above has a hearing loss averaging (C.A.L. method) more than 10 or 11 db. Also none of the losses of these ears at 2000 or 1000 cps is greater than 20 db. The effect of these small losses on everyday hearing, especially hearing for speech, is negligible.

Regarding the pathological significance of the losses and the question of the need for medical treatment, the only medical 'abnormality' discovered in the subsequent E.N.T. examination of the two cases available are enlarged tonsils, the enlargement being within the limits of normal fluctuation and no medical action being required. Unfortunately the other two cases were not available for medical examination at the time.

Thus in the few cases discovered with hearing losses at 2000 and/or 1000 cps only (and passing the screening test at 4000 and 500 cps) the average hearing losses of each case were small and of little practical significance, and no medical treatment was required at least in the two cases medically examined.

Therefore, the additional time required to screen all ears at 2000 and 1000 cps as well as at 4000 and 500 cps (with consequently substantially slower rates of testing –see relevant results below) does not seem warranted in a regular school audiometric screening program, although it may be warranted for research or other purposes.

## THE COMPARATIVE RATES OF TESTING ATTAINED WITH THE THREE SCREENING TECHNIQUES

Another measure of the comparative efficiency of the three different frequency–intensity screening techniques is the relative rates of testing attainable with them. Whilst being of subsidiary importance relative to the efficiency of the techniques in discovering hearing losses, nevertheless rates of testing are a significant 'economic' consideration in deciding the relative merits of screening techniques.

We were concerned with comparing rates of testing per actual hour worked rather than per working day because each of the three screening techniques requires identical general preliminary arrangements with schools etc. and we already had much data on this matter from the previous survey.

The data from which comparative statistics arise is as follows:

NUMBERS TESTED AND TIMES FOR THREE DIFFERENT SCREENING TECHNIQUES

Screening at 15 Db at 4000, 2000, 1000 and 500 Cps

| Ainslee Public School | | | | Telopea Park Public School | | | | Grand Totals | |
|---|---|---|---|---|---|---|---|---|---|
| Date and Grades | Time Taken Hours | Mins. | No. | Date and Grades | Time Taken Hours | Mins | No. | Time | No. |
| 24/11/52 Gr.3 | 2 | 40 | 81 | 24/11/52 Gr. 3 | | 35 | 10 | | |
| 24/11/52 Gr.3–4 | 4 | 50 | 114 | 25/11/52 Gr. 3 | 4 | 25 | 112 | | |
| 26/11/52 Gr. 4 | 1 | | 45 | 26/11/52 Gr. 3 | | 30 | 22 | | |
| 27/11/52 Gr. 6 | 1 | 05 | 32 | 28/11/52 Gr. 6 | 2 | 25 | 84 | | |
| 28/11/52 Gr. 6 | | 55 | 69 | 28/11/52 Gr. 2 | | 40 | 62 | | |
| 28/11/52 Gr. 2 | 4 | | 110 | | | | | | |
| Totals: | 14 | 30 | 451 | | 8 | 35 | 290 | 23–5 | 741 |
| Screening at 15 Db at 4000 cps and 500 cps | | | | | | | | | |
| 26/11/52 Gr. 4–5 | 2 | 25 | 75 | 26/11/52 Gr. 4 | 1 | 55 | 59 | | |
| 27/11/52 Gr. 6 | 1 | 35 | 29 | 27/11/52 Gr. 5–6 | 1 | 20 | 59 | | |
| Totals: | 4 | | 104 | | 3 | 15 | 118 | 7–15 | 222 |
| Screening at 15 Db at 4000 Cps and 20 Db at 500 Cps | | | | | | | | | |
| 26/11/52 Gr. 5 | 1 | 20 | 50 | 26/11/52 Gr. 4–5 | 1 | 55 | 77 | | |
| 27/11/52 Gr. 5 | | 55 | 50 | 27/11/52 Gr. 5 | 1 | 25 | 78 | | |
| Totals: | 2 | 15 | 100 | | 3 | 20 | 155 | 5–35 | 255 |
| Grand Totals: | 20 | 45 | 655 | | 15 | 10 | 563 | 35–55 | 1218 |

Extracting from this table and calculating rates of testing per hour we obtain the following table:

ACTUAL TESTING RATES FOR THREE DIFFERENT TECHNIQUES

Screening at 15 Db at 4000, 2000, 1000, and 500 Cps

| Ainslee Public School (R.W.) | | | | Telopea Park Public School (R.F.) | | | | Totals | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time in Hrs | Mins. | No. | Rate/Hr | Time in Hrs | Mins. | No. | Rate | Time | No. | Rate |
| 14 | 30 | 451 | 31.1 | 8 | 35 | 290 | 33.8 | 23–5 | 741 | 32.1 |
| Screening at 15 Db at 4000 and 500 Cps | | | | | | | | | | |
| 4 | | 104 | 26.0 | 3 | 15 | 118 | 36.3 | 7–15 | 222 | 30.6 |
| Screening at 15 Db at 4000 and 20 Db at 500 Cps | | | | | | | | | | |
| 2 | 15 | 100 | 44.4 | 3 | 20 | 155 | 46.5 | 5–35 | 255 | 45.7 |
| Totals | | | | | | | | | | |
| 20 | 45 | 655 | 31.6 | 15 | 10 | 563 | 37.1 | 35–55 | 1218 | 33.9 |

(a) Results

(1) Rates of Screening at 15 Db at 4000, 2000, 1000, and 500 Cps versus at 15 Db at 4000 and 5000 Cps

The difference between the hourly rate of screen testing of children at 15 db at 4 2, 1, and .5 kc (32.1 children per hour) versus rate of screening at 15 db at 4000 and 500 cps only (30.6 children per hour) is not statistically significant. (Using Chi–Square technique, P is .60 or 60%.) However, our previous survey showed that rates of screening are mainly affected by age levels of children tested and also by incidence of hearing loss (besides screening method.)

The age levels of the children in the two samples is reasonably controlled and 'matched' by the experimental design.

However, the percentage incidence of ears failing the screen test and therefore requiring full descending threshold tests at five frequencies differs considerably in the two samples, namely 6.0% in the first sample and 10.4% in the second. Percentage incidence of ears rather than children failing the screen tests is the more relevant statistic because only ears failing are fully tested so that a case with binaural loss takes nearly twice as long to test as a case with unilateral loss.

These differences in percentage incidence of cases failing the screen test cannot be accounted for by the use of different screening methods because the intensity levels used are identical (15 db above threshold) and the screening at four frequencies versus at two frequencies would, other things being equal, tend to cause a higher rather than a lower percentage of children to fail the screen test. It is, of course, impossible to pre–control incidence of hearing loss in two samples in an investigation such as this.

However, a method of controlling hearing loss after the event in this study is to calculate what the testing rates would have been with an equal, arbitrarily chosen typical average percentage incidence of ears failing the screen tests, e.g., 5% of ears.

Therefore, in the following table we have done this by calculating the number of ears in each sample that would have failed the screen test to average 5% incidence of ears failing, conservatively allowing four minutes to fully test each ear differing from this number and recalculating rates of testing accordingly (called 'Adjusted Rates of Screening'):

ADJUSTED TESTING RATES

Screening 15Db at 4,2,1,.5 Kcps

Versus 15Db at 4 and .5 Kcps

| Screening Technique | Testing in Hrs–Min | | No. Tested (children) | No. Failing (ears) | No. Ears Failing Adjusted for 5% Incidence | Adjusted Screening Rate/Hr |
|---|---|---|---|---|---|---|
| 15Db at 4,2,1,.5 Kcps | 23 | 5 | 741 | 89 | 74 | 33.5 |
| 15 Db at 4 & .5 Kcps | 7 | 15 | 222 | 46 | 22 | 39.2 |

The difference between these adjusted hourly rates of testing per hour is statistically significant, using the Chi–Square Technique (P almost 0.05, i.e., less than 5%).

Moreover, the difference in hourly rates of testing of about five or six children per hour is of practical significance in that it shows that children can be screened substantially faster (about 15% faster) screening at only two frequencies versus screening at four frequencies. However, the question whether a considerable number of children with hea. defects is missed by using the former rather than the latter method remains and is considered later.

An interesting confirmation of the legitimacy of adjusting testing rates to allow for different incidences of ears failing the screen test in the two samples is given by the fact that in testing at Telopea Park School R.F. obtained a testing rate of 33.8 children per hour, with 5.5% of ears failing, screening at four frequencies, versus a testing rate of 36.3 children per hour, with an only slightly larger incidence of 6.8% of ears failing screening at two frequencies.

(2) Rates of Testing Using 15 Db at 4 and .5 Kcps Versus 20 Db at .5 Kcps and 15 Db at 4 Kcps

The actual hourly rate of testing using 15 db at 4000 and 500 cps (30.6 per hour) is statistically very significantly lower than the rate using 20 db at 500 cps and 15 db at 4000 cps. (Using Chi–Square, P is 0.0, i.e., 0.1%.)

However, the incidence of ears failing using the former method (10.4% ears is more than twice that using the latter method (4.1% ears). This great difference in percentage incidence of ears failing is not accounted for by the difference in screening intensity levels (see later.)

Adjusting these screening rates as explained above for equal (5%) incidence of ears failing, the following table is obtained:

ADJUSTED TESTING RATES
Screening at 15 Db at 4 & .5 Kcps, Vs
20 Db at .5 Kcps and 15 Db at 4 Kcps

| Screening Technique | Testing in Hrs–Min | | No. Tested (children) | No. Failing (ears) | No. Ears Failing Adjusted for 5% Incidence | Adjusted Screening Rate/Hr |
|---|---|---|---|---|---|---|
| 15 Db at .5 & 4 Kcps | 7 | 15 | 222 | 46 | 22.2 | 39.2 |
| 20 Db at .5 & 15 Db at 4 Kcps | 5 | 35 | 255 | 21 | 25.5 | 43.3 |

The adjusted testing rate using 15 db at 500 and 4000 cps (39.2 pr hour) is not statistically significantly lower than that using 20 db at 500 cps and 15 db at 4000 cps (43.3 per hour). (Using Chi–Square, P is 0.28, i.e., 28% level.)

However, if the relative effectiveness of these two screening methods in picking up minor hearing losses is taken into account and corresponding different incidence rates allowed, the small difference in testing rate may become just statistically significant. This difference in effectiveness is considered later.

(b) Summary of Findings on Rates of Testing Per Hour

Adjusting the hourly rates of audiometrically testing children for comparability under various experimental conditions by allowing for a standard incidence of 5% of ears failing the screen test and requiring full air conduction descending threshold tests (allowing four minutes per ear), we obtain the following findings:

(1) Using the method of screening at 15 db at 4000, 2000, 1000 and 500 cps, a mean adjusted rate of testing of 33.5 children per hour was obtained.

(2) Using the method of screening at 15 db at 4000 and 500 cps, a mean adjusted rate of testing of 39.2 children per hour was obtained, which is statistically significantly higher than that obtained using the first screening method.

(3) Using the method of screening at 15 db at 4000 cps and 20 db at 500 cps a mean adjusted testing rate of 43.3 children per hour was obtained. This rate is not significantly higher.

These findings would have been modified slightly if analysis of the rest of the data had shown that the three screening techniques intrinsically discover significantly different rates of incidence of hearing defects (i.e., that they resulted in different proportions of children failing the screen tests) so that the adjustment of hour-

ly rates of testing to a standard incidence of 5% of ears failing would not have been entirely legitimate.

However, as already shown, the three screening techniques discovered only very slightly different minima or patterns of hearing loss (e.g., the technique using 15 db at all four frequencies identified only an extra 0.3% of all ears as having hearing losses as compared with screening at 15 db at .5 and 4 kcps only). We can now sum up:

### Conclusions on the Relative Merits of the Three Screening Techniques

Our findings on the relative merits of the three screening techniques are summarized in the following table:

SUMMARY TABLE

| Screening Technique | Extra Hearing Defects Found | Importance of Extra Losses | Adjusted Rate of Testing | Practicability |
|---|---|---|---|---|
| 15 Db all frequencnes | 0.3% more | nil | 33.5 | Satis. |
| 15 Db at .5 & 4 Kcps | Standard | | 39.2 Sig. Not Sig. | Satis. |
| 15 Db at 4 Kcps, 20 Db | 0.5% less | nil | 43.3 | Adeq. |

In view of these findings, indications from our pilot experiment on screening intensity levels, and clinical experience, we therefore advocate the use of tones of 4000 and 500 cps at 15 db sensation level in screen testing hearing of children in schools. However, where noisy testing conditions are encountered, it may be necessary sometimes to increase the intensity level to 20 db sensation level at 500 cps. Screening is not advised under extremely noisy testing conditions.

## INCIDENCE AND TYPES OF HEARING DISORDERS IN CHILDREN

### Introduction

One of the objects of our survey was to learn the incidence of hearing disorders of a substantial and representative number of the children in schools and kindergartens in Canberra.

Whilst it may be argued that the Canberra population is not perfectly representative of the Australian population as a whole because it includes an unusually large proportion of public servants of above average socio-economic status, nevertheless, at the time of our surveys (1951–2), Canberra included considerable numbers of building and gardening workers and also foreign language speaking immigrants, and was probably not very unrepresentative of the general Australian population with respect to deafness. An exception may be that there appeared to be evidence from our laboratories' clinical records in Sydney that several profoundly deaf children had been sent out of Canberra (where there were no special schools for the deaf) to attend schools for the deaf in Sydney, etc.

### The Incidence of Hearing Disorders

The most representative findings on the incidence of hearing dis-

orders in children in Canberra schools and kindergartens were given by our first survey in 1951, in which we screen tested the hearing of 2,618 chil – dren at all educational levels, probably covering about two–thirds of the school and kindergarten population in Canberra at the time.

The pre–school kindergartens and schools at which we then tested have already been listed here. The following tables show the incidence of children and ears failing the screen test involving tones of 15 db sensation level (A.M.A. Standards) at 4000 cps and 15–20 db at 500 cps and confirmed by full air conduction thresholds testing to have hearing losses.

The first table shows the incidence of hearing losses at the various pre–school and school educational levels, the age ranges mentioned being approximate only:

INCIDENCE OF HEARING LOSS AT VARIOUS EDUCATIONAL LEVELS

| Grade and Approx. Age | No. | One Ear Failing | Both Ears Failing | Total Children Failing | Total Ears Failing | Percentage (Children) | Incidence (Ears) |
|---|---|---|---|---|---|---|---|
| Pre–School 3–5 Yrs | 136 | 4 | 2 | 6 | 8 | 4.41 | 2.94% |
| Primary 5–9 Yrs | 774 | 19 | 4 | 23 | 27 | 2.97 | 1.74 |
| Grades 3–6 10–12 Yrs | 1051 | 47 | 19 | 66 | 85 | 6.28 | 4.04 |
| Secondary 13–17 | 657 | 28 | 2 | 30 | 32 | 4.57 | 2.44 |
| Totals: | 2618 | 98 | 27 | 125 | 152 | 4.77 | 2.90 |

In view of the overlap between ages and educational levels, the incidence of hearing loss at various ages of children is tabulated below:

INCIDENCE OF HEARING LOSS AT VARIOUS AGE LEVELS

| Age in Years | No. | Numbers Failing Screen Test: One Ear | Both Ears | Total Children | Total Ears | Percentage (Children) | Incidence (Ears) |
|---|---|---|---|---|---|---|---|
| 2 | 1 | | | | | | |
| 3 | 41 | 3 | 1 | 4 | 5 | 9.76 | 6.10% |
| 4 | 133 | 1 | 1 | 2 | 3 | 1.5 | 1.13 |
| 5 | 257 | 6 | 3 | 9 | 12 | 3.5 | 2.33 |
| 6 | 267 | 8 | 1 | 9 | 10 | 3.37 | 1.87 |
| 7 | 250 | 7 | | 7 | 7 | 2.80 | 1.40 |
| 8 | 260 | 7 | 1 | 8 | 9 | 3.08 | 1.73 |
| 9 | 287 | 16 | 5 | 21 | 26 | 7.32 | 4.53 |
| 10 | 230 | 9 | 5 | 14 | 19 | 6.09 | 4.13 |
| 11 | 216 | 7 | 5 | 12 | 17 | 5.56 | 3.94 |
| 12 | 206 | 14 | 5 | 19 | 24 | 9.22 | 5.83 |
| 13 | 171 | 6 | | 6 | 6 | 3.51 | 1.75 |
| 14 | 180 | 8 | | 8 | 8 | 4.44 | 2.22 |
| 15 | 71 | 4 | | 4 | 4 | 5.63 | 2.82 |
| 16 | 41 | 2 | | 2 | 2 | 4.88 | 2.44 |
| 17 | 6 | | | | | | |
| 18 | 1 | | | | | | |
| Tot: | 2618 | 98 | 27 | 125 | 152 | 4.77 | 2.90 |

Statistical analysis of this table reveals that there is very probably some relationship between the incidence of ears with hearing loss and ages of the children (the probability of the null hypothesis being true is less than 0.001).

Inspection of this and the preceding table indicates a consistent increase in hearing disorders in children aged from 9 to 12., i.e., in the upper primary grades. The causes of such increased incidence are obscure.

The overall incidence of 4.77% of children or 2.90% of ears tested having some measurable hearing losses at the frequencies tested is fairly closely in accord with the central tendency of the findings reported in the American literature (see Watson and Tolan, 23, p. 236, and also Dahl, 3, p. 5). However, before it is concluded that the allegedly superior average socio-economic status and medical services of the Canberra population have not reduced the incidences of hearing loss, it must be remembered that status of the incidence of hearing loss in Australian children in general is or was not available. Our subsequent audiometric survey of children in three kindergartens in the inner suburbs of Sydneyhaving low socio-economic status showed 17.6% of children and 13.7% of ears to have some hearing loss. However, we must wait more representative Australian statistics to enable any geographical comparisons to be made.

It is worth remarking that our initial Canberra survey took place in summer, whereas American findings by Lutz (16) indicate that the incidence of hearing losses in school children increased significantly in winter, although only by small percentages. In Canberra, Dr. Clement subsequently obtained the clinical impression that there were considerably higher incidences of allergic conditions and hearing losses in school children there during winter.

Only six out of 2618 children screen tested, i.e., only 0.002%, had binaural hearing losses of over 30 db in the better ear, i.e., sufficient to hamper communications considerably and two of these were wearing hearing aids fitted by our laboratories. Such incidence is very low as compared with the incidence of such cases reported in Watson and Tolan (23). As already stated, we know that several profoundly deaf children from Canberra had been sent to schools for the deaf in Sydney.

Types of Hearing Disorders and Their Etiology

Regarding the types of hearing losses found in our original survey, it is apparent from the preceding tables that over three times as many children had monaural as against binaural hearing losses.

The degrees and ranges of average hearing losses found in the initial survey (in which 2618 children were screened) are tabulated below. (The C.A.L. definition of an average loss of an ear is the average of the decibel hearing losses in that ear through the three audiometric octaves from 500 to 4000 cps, which are important in the audiometry perception of speech.)

THE DEGREES AND TYPES OF AVERAGE HEARING LOSSES FOUND IN INITIAL SURVEY (Children from Kindergarten to leaving Standards)

| Type of Hearing Loss | No. | Mean Ave. Loss | Median Ave. Loss | Range (Db) | No. with Over 30 Db Loss in Better Ear |
|---|---|---|---|---|---|
| Monaural | 98 | 22.4 | 16 | 3–88 | 0 |
| Binaural | | | | | |
| Better Ear | 27 | 22.7 | 19 | 8–16 | 6 |
| Worse Ear | | 31.0 | 28 | 11–83 | |

However, a less extreme predominance in incidence of monaural over binaural hearing losses appeared in the second survey (in which 1218 children were screened) as the following table shows

DEGREES AND TYPES OF AVERAGE HEARING LOSSES FOUND IN SECOND SURVEY
(Children from Primary Grades 2 to 6)

| Type of Hearing Loss | No. | Median Ave. Loss | Range (Db) | No. with Over 30 Db Loss in Better Ear |
|---|---|---|---|---|
| Monaural | 68 | 12 | 2–78 | |
| Binaural (Better Ear) | 44 | 12 | 2–55 | 6 |

Note: The average hearing losses referred to are mainly the figures obtained on retest about two weeks after screening.)

It may be noted that in this latter survey, the percentage incidence of ears failing the screening was unusually high at 6.4%, even when compared with the results of the previous survey for the equivalent primary Grades 2 to 6 which showed a significantly high incidence of hearing disorders, although our later survey took place in summer (late November) the period during which we tested was characterised by unusually cold and windy conditions which Dr. Clement considered to be likely to provoke respiratory allergies.

## CONCLUSIONS AND RECOMMENDATIONS

The following general conclusions and recommendations are derived from our experimental audiometric surveys of the hearing of children in the schools and kindergartens of Canberra and from the Australian Capital Territory School Medical Service in applying our recommended methods of audiometric screening as part of its regular medical examination in schools

1. The hearing of children in schools and preschool kindergartens can be tested economically and efficiently with pure tone screening audiometry, using an audiometer such as the Commonwealth Acoustic Laboratories Type B1 portable battery model, applied individually with appropriate techniques.

2. The general audiometric method we recommend for such testing is to screen test, with appropriate techniques, the hearing of children in each ear, first at 15 decibels (db) sensation level (American Medical Association and Australian standards) at a tone of 4000 cps and then at 15 db at 500 cps – or occasionally at slightly higher sensation levels if ambient noise levels are unusually high but not high enough to preclude adequate screening.

3. A moderately trained audiometrist engaged fully in audiometric screening (including the taking of full air conduction audiograms on children failing the screen test) can test at the rates of from approximately 15 children per working hour at the preschool kindergarten levels, and 36 children per hour in the first half of primary school, up to 63 children per hour at the secondary school levels.

4. Incidences of measurable hearing defects can be expected of the order of about 5% of ears or 3% of children audiometrically screened, incidence varying considerably with population characteristics such as socio–economic status and probably with seasons, winter appearing to be associated with greatest incidence.

5. Most hearing losses ascertained by such screening are monaural, and most of all hearing losses are slight to moderate conductive deafnesses amenable to medical treatment. Also, a considerable proportion of hearing losses occur in young children that are at least partly liable to eventual spontaneous recovery.

Marked binaural hearing losses (i.e., average more than 30 db in the better ear) identified by our screening surveys were relatively rare (e.g., 0.23%), but the population may already have 'selected' itself in this respect by some very deaf children having been sent to other cities, so that considerably higher incidences may occur elsewhere and at different times, depending on epidemics, etc.

6. Such pure tone audiometric screening of children is quite practicably carried out as an integral part of the regular general medical examinations of children in schools by school medical services. The actual screen testing is conveniently performed by an appropriately trained school medical service nurse working under the supervision of, and in conjunction with, the service doctor.

7. Medical and other rooms used for audiometric screening should be as quiet as practicable, carpeted and furnished with a chair, table and seating form.

8. Audiometric screening of children by school medical services should be carried out, as part of the regular general medical examinations of school children at the early stages of primary school, such as Grades 1 and 3, and perhaps at 6, and desirably at second or third year of secondary school (to help ensure a pre-vocational check and perhaps in fifth year.

9. To help ensure adequate medical, educational and social treatment of children identified with hearing loss, it is necessary to interpret and communicate audiometric findings to parents, teachers and medical practitioners, and ultimately to develop a community informed by those who know about such matters.

ACKNOWLEDGMENTS

Our sincere gratitude is due to Dr. Edith Clement, School Medical Officer, Department of Health, Canberra, for her very helful and most amiable collaboration in these studies including implementation of the new method over a long period. Our thanks are due also to the principals and staffs of the schools and 'play centres' in Canberra who facilitated arrangements, and to the children who usually cooperated so eagerly.

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# Audiological Findings in an Unusual Case of VIIIth Nerve Lesion

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The accumulation of substantial case material with surgically confirmed VIIIth nerve lesions is difficult because of the comparative rarity of suitable patients for study, and the fact that surgical confirmation ordinarily comes only after auditory tests have been completed.

In the spring of 1959 an unusual opportunity to study auditory function in an already surgically-confirmed unilateral VIIIth nerve lesion arose. The patient, a 58-year old female, was hospitalized in February, 1959, because of a suspected right acoustic neuronoma. Fig. 1A shows an audiogram made on February 18, 1959, revealing essentially normal pure-tone acuity in the left ear, but almost no measurable hearing in the right ear. A subsequent operation revealed a massive meningioma in the right cerebellopontine angle. The eighth nerve could not be observed, either before or after removal of the meningioma, and was assumed to be totally destroyed. However, as will be shown, this observation was inaccurate. Subsequent tests show that although the VIIIth nerve was severely damaged by the tumor, it was not destroyed either by the tumor or the operation.

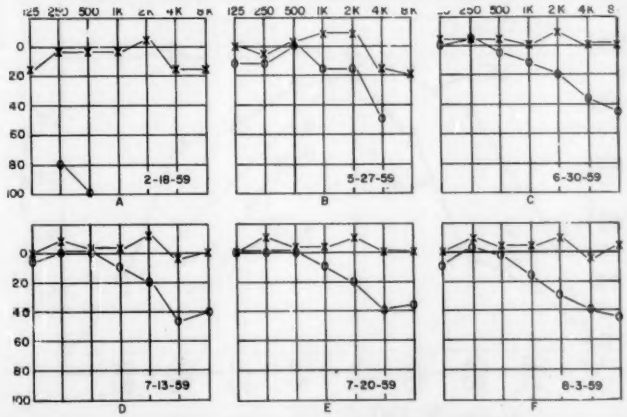


FIG. 1: PRE– AND POSTOPERATIVE AIR CONDUCTION AUDIOGRAMS
A....PRE–OP, B–F....POSTOP

Approximately two weeks post-operatively, the patient became aware of 'depth' in her hearing and felt that her ability to localize the direction from which sounds came had improved noticeably. During the next two months she was aware of progressive improvement in the right ear. Fig. 1B shows an audiogram made on May 27,1959. The post-operative improvement is quite remarkable. Periodic audiograms taken over the next two months (Figs. 1C through 1F) show slight further improvement followed by a relatively stabilized level.

Thanks to the patient's very generous willingness to cooperate in rather lengthy test sessions, it was possible to amass a large body of data relevant to several aspects of auditory function on the right ear. Matching data on the left ear served as control observations.

## Speech Audiometry

Fig. 2 shows the articulation function for PB-50 word lists on each ear. These tests were made on June 30, 1959. The abscissa of this figure is the intensity level of the speech in decibels above the spondee threshold. Intensity levels were based on spondee threshold hearing levels of 0 decibels in the left ear and 14 decibels in the right ear. During all right ear testing the left ear was masked by noise at an overall sound pressure level of 82 decibels. Tests were also run at levels of 10, 20, 30, and 40 decibels in the right ear without masking in the left ear. Results were essentially unchanged.

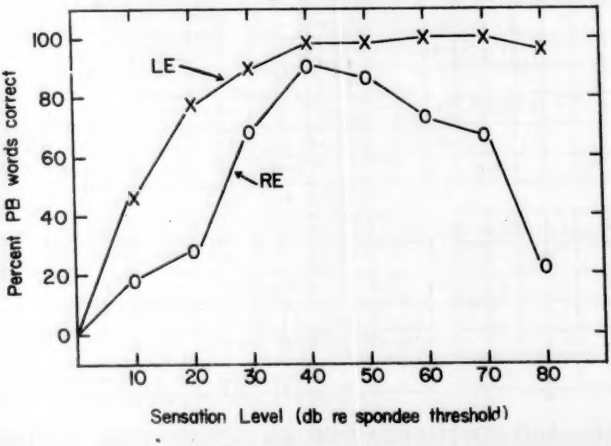


FIG. 2. ARTICULATION FUNCTIONS FOR PB-50 WORD LISTS

The function for the left, or normal, ear rose steeply to a maximum near 100% at the 40–decibel level and remained high out to the 80–decibel level. The right ear, however, showed a very peculiar phenomenon. As intensity increased the function rose less steeply than the left ear, reached a maximum of 90% at the 40–decibel level, then rather rapidly decreased to a score of only 22% at the 80–decibel level. As a check on the reliability of this last score, the identical procedure was repeated on July 6 and July 27, 1959. Scores were 28% and 16% respectively.

These results illustrate dramatically what appears to be a rather fundamental principle recently elucidated by Schuknecht (1), namely, that an VIIIth nerve lesion may have a profound effect on the ability to understand PB words in the face of relatively slight loss in acuity for pure tones.

## Binaural Balance Tests

Fig. 3 shows the results of alternate and binaural simultaneous balance tests at 4000 and 6000 cps. At both frequencies the tone was fixed at a given sensation level on the right ear, and the patient varied the intensity of a tone identical in frequency on the left ear until the two were equally loud (alternate balance) or until the phantom image was centered in the median plane (simultaneous balance). Four sensation levels, 10, 20, 30, and 40 db were explored. The exact details of instrumentation and procedure are given in Jerger and Harford (2).

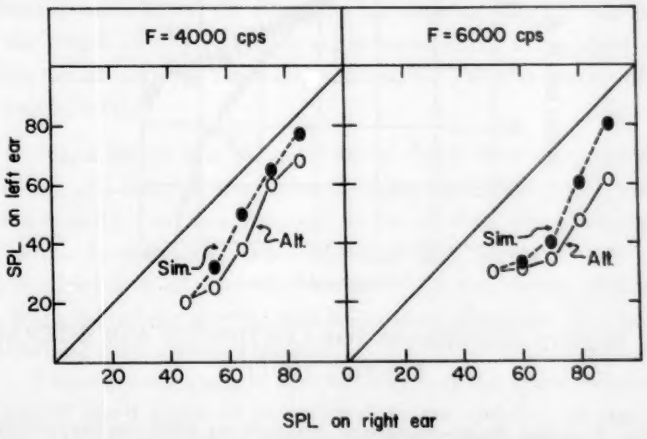


FIG. 3. ALTERNATE AND SIMULTANEOUS BINAURAL BALANCE TESTS

Fig. 3 shows that recruitment (ALT) is clearly absent on the right ear. The result of median–plane–localization tests (SIM) for tones presented simultaneously to the two ears shows that, at all levels, the patient required more intensity on the left ear for median–plane localization than for equal loudness. At some levels the difference between alternate and simultaneous matches amounted to 20 db. This finding appears to be quite common in unilateral VIIIth nerve lesions. Its possible significance for auditory theory is discussed by Jerger and Harford (2).

### Bekesy Audiometry

Fig. 4 shows Bekesy conventional tracings for both periodically interrupted (I) and continuous (C) tonal stimuli on the right ear. Both these and subsequently drawn fixed–frequency tracings were all obtained on a Grason–Stadler Model E–800 Bekesy audiometer, with a chart speed of one minute per octave and an attenuation speed of 2.5 db/sec. The two tracings (C and I) for the left ear overlapped in the normal fashion. On the right ear, however, Fig. 4 shows that the continuous tracing (C) begins to break away from the interrupted at about 1500 cps and rapidly drops to the audiometer limit in less than two octaves.

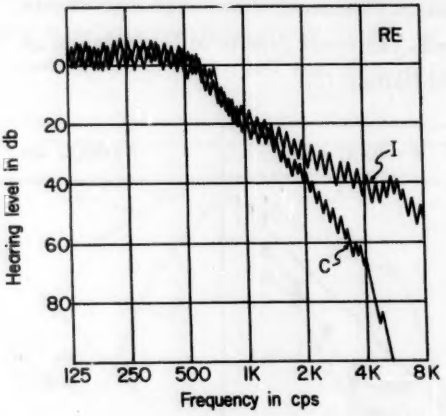


FIG. 4. BEKESY AUDIOGRAMS FOR CONTINUOUS AND INTERRUPTED TONAL STIMULI

Fig. 5 shows fixed–frequency tracings at 4000 cycles/second, for three minutes, on each ear. Again, the two tracings (C and I) overlap on the left ear. On the right ear, however, although the interrupted tracing remains horizontal, the continuous tracing drops rapidly to the limit of the audiometer in less than 60 seconds.

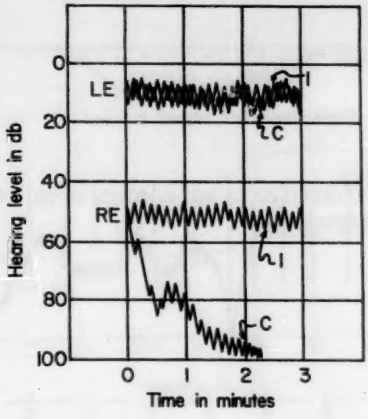


FIG. 5. THREE–MINUTE FIXED–FREQUENCY BEKESY TRACINGS AT 4000 CPS

In view of the startling difference between continuous and interrupted tracings, an effort was made to determine whether there was a minimum 'off' period between successive short tones above which the tracing would remain stable and below which it would begin to drop over time. To this end, the output from an audio–oscillator was sent through a Grason–Stadler Model 829 electronic switch, triggered by a Grason–Stadler Model 470 electronic interval timer. The switched output was then passed through the Bekesy audiometer. By adjusting the interval timer it was possible to vary the length of the silent interval between successive short tones while keeping the on–duration constant at 200 msec. The rise–decay of each short tone was 50 msec.

Fig. 6 shows this patient's actual fixed–frequency tracing at 4000 cps as the off–duration was systematically varied. No appreciable change in the threshold level was observed as the off–time was decreased from 300 to 20 msec. At shorter off–times, approximately 15 and 10 msec., there was a rapid initial drop of about 10 db after which the tracing stabilized quite well. When the silent interval was eliminated altogether (C), however, the characteristic drop always appeared.

These results suggest that the length of the silent interval between successive short tones is not critical to the stability of the interrupted tracing. Apparently, only a very minimal rest period is sufficient between successive stimuli to ensure a stable tracing.

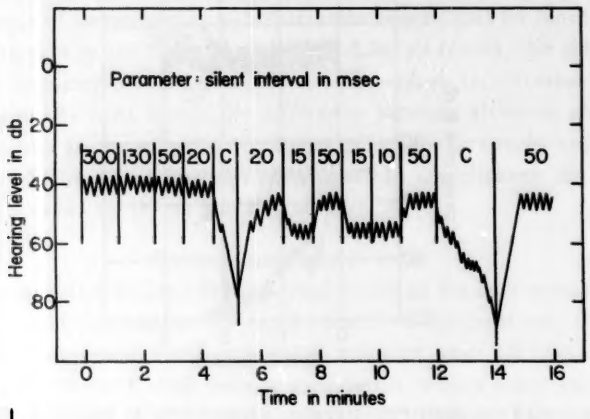


FIG. 6. FIXED-FREQUENCY BEKESY TRACING AT 4000 CPS ON THE RIGHT EAR WITH VARYING SILENT INTERVAL BETWEEN SUCCESSIVE SHORT TONES

Masking of Pure Tones by Thermal Noise

In order to test Langenbeck's (3) hypothesis that thermal noise will produce an abnormally great amount of masking in the ear with VIIIth nerve pathology, pure-tone thresholds were measured in each ear in quiet and in the presence of thermal noise at an overall SPL of 80. All thresholds were measured by the method of adjustments, using a 2-db step attenuator. Threshold was always defined as the average of three separate intensity adjustments. Exact procedural details are summarized in Jerger, Tillman, and Peterson(4).

Fig. 7 shows the threshold SPL in each ear at five frequencies in the presence of this masking noise. No appreciable difference between ears is apparent.

As a further check on the possibility of abnormal masking phenomena in the right ear, pure-tone masking was measured in the presence of bandpass-filtered thermal noise. Thermal noise was first passed through a passive-network filter with an attenuation characteristic of approximately 70 db per octave, then adjusted to give an effective level (z) on the test ear. Figs. 8 and 9 show the masking produced in each ear by the two pass bands, 400-800 cps at an effective level of 60 db, and 1200-2400 cps at an effective level of 30 db. For the low band 400-800) z was computed

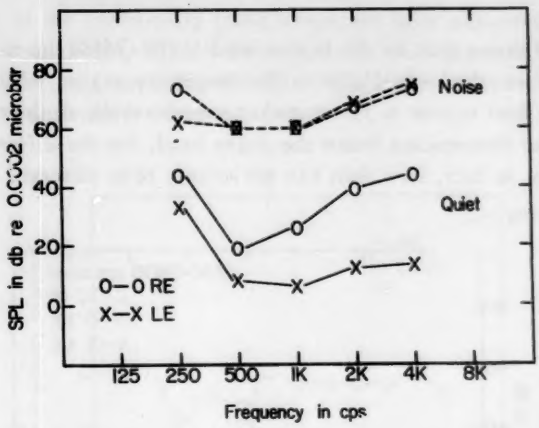


FIG. 7. PURE–TONE MASKING PRODUCED BY BROAD–BAND THERMAL NOISE AT AN EQUAL OVERALL SPL ON EACH EAR

relative to the threshold SPL in quiet at 500 cps. For the high band (2400–2400 cps) z was computed relative to the threshold SPL at 2000 cps.

Fig. 8 shows that, in the low–band noise, the masking functions for the two ears are dissimilar, but in an unexpected direction. The bad ear shows less, rather than more, masking than the good ear; however,this occurs only in the frequency region between 750 and 2000 cps and is probably not signi ficant.

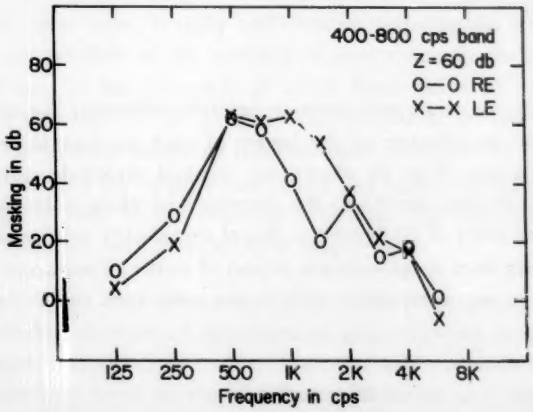


FIG. 8. PURE–TONE MASKING PRODUCED BY OCTAVE–BAND THERMAL NOISE NOISE (1200 – 2400 CPS) AT Z (EFFECTIVE MASKING) OF 60 DB ON EACH EAR

Fig. 9 shows that for the higher band (1200–2400) the two ears yield very similar results, especially in the frequency region within the noise band. There does appear to be somewhat more masking on the right ear than on the left for frequencies below the noise band, but the difference is very slight and is, in fact, less than has previously been observed in ears with cochlear lesion (4).

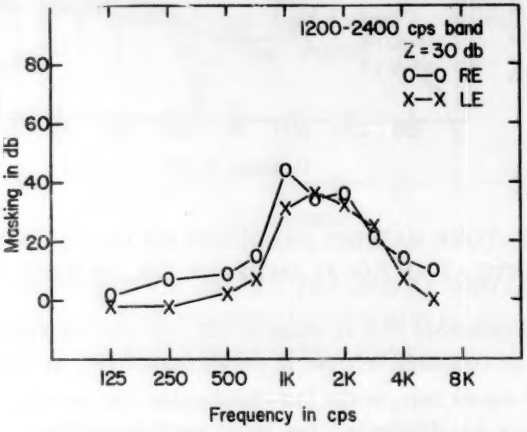


FIG. 9. PURE–TONE MASKING PRODUCED BY OCTAVE–BAND OF THERMAL NOISE (1200 – 2400 CPS) AT Z (EFFECTIVE MASKING) OF 30 DB ON EACH EAR

Finally, an effort was made to determine whether the masked threshold SPL might be affected by the length of time the masking noise stimulated the right ear. Fig. 10 shows the masked threshold sound pressure level for 4000 cycles/second in the presence of white noise at an overall sound pressure level of 80 decibels. Tonal thresholds were measured at one minute intervals over a ten–minute period of noise stimulation. There does not appear to be any systematic shift in the pure–tone threshold over time.

## Discussion

This patient provided a unique opportunity to explore a number of currently controversial aspects of auditory behavior in a case of surgically–confirmed VIIIth nerve lesion.

Many of the classically cited symptoms were observed. Loudness recruitment was absent, speech discrimination was impaired in an extraordinary fashion, and marked threshold adaptation under continuous stimulation was dramatically evident.

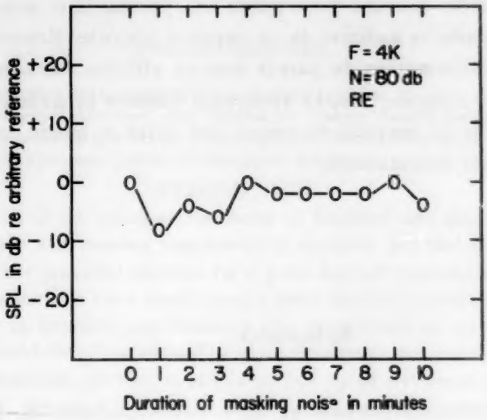


FIG. 10 MASKED THRESHOLD SPL AT 4000 CPS IN RIGHT EAR DURING 10 MINUTES OF SUSTAINED THERMAL NOISE AT AN OVERALL SPL OF 80 DB

On the other hand, lengthy and detailed exploration failed to demonstrate any abnormality in the masking of pure tones by thermal noise on the impaired ear. In the presence of broad band noise at equal overall level, masked threshold SPLs were virtually identical on the two ears. In the presence of octave–bands of thermal noise at equal effective levels, the spread of masking for frequencies above and below the band was, if anyanything, slightly less on the impaired side than has been previously observed (4) in cochlear loss of equivalent magnitude.

## Summary

Remarkable recovery of pure–tone acuity following surgical removal of a meningioma in the right cerebellopontine angle provided a unique opportunity to study several facets of auditory behavior in a single patient. Loudness recruitment was absent, speech discrimination was extraordinarily affected, and severe threshold adaptation under continuous stimulation

was apparent. No abnormality in the masking of pure tones by either broad or narrow band noise could be demonstrated.

Summario in Interlingua

Recuperation remarcabile de audienta tonal post remotion de un meningioma in le angulo cerebello–pontine presentava un opportunitate unic studer aspectos plure de conducta auditive in un patiente singule. Recrutamento esseva absente, discrimination de parola esseva afficite extraordinarimenta, e adaptation sever a limine esseva apparente durante stimulation continue. Nulle aberration in le mascar de tonos con ruito o bando late o banda stricte poteva esser demonstrate.

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# THE EFFECTIVENESS OF BINAURAL HEARING FOR ADULTS WITH HEARING IMPAIRMENTS*

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## INTRODUCTION

The question of the comparative value of binaural and monaural amplification for individuals with hearing impairment is not new. But the advent of transistor hearing aids has provided impetus for a good deal of speculation. Both clinicians and research workers have manifested a great deal of interest in this problem. Genuine interest in binaural amplification was manifested as early as 1912 (23). In 1952 Hirsh stated that "we should have each microphone mounted right next to its associated earphone, so that sound is picked up at the usual place (near the ear)" (25, p. 241). Bergman indicated certain advantages of binaural amplification:

> The startling progress recently in the reduction of the size of hearing aids, particularly since the advent of the transistor, has stimulated renewed interest in the production of binaural hearing aids--such as hearing aid eyeglasses with complete, separate instruments on each side of the head--which would closely approximate nature's design for two-eared hearing (2, p. 12).

Under both simple and complex listening conditions two ears provide better efficacy than one for the individual with normal hearing (23, 25, 29, 36). Different investigators have reported binaural superiority in areas of threshold of audibility (24, 27, 42, 47), loudness summation (9, 19), speech intelligibility (3, 11, 17), masking (23, 26, 29, 32, 36, 37), and localization (17, 35, 36, 45).

Hirsh (23) and others (2, 30, 49) agree on:

1. probable advantages of binaural over monaural amplification,
2. probable advantages of binaural over pseudo-binaural amplification, or the use of one microphone, one amplifier, and two earphones.

An examination of the literature does not unequivocally indicate pseudo-binaural amplification to be without value.

One suggested advantage of binaural hearing (over pseudo-binaural) concerns the ability of a binaural listener to suppress effectively interfering signals when listening for a specific stimulus. Koenig reported binaural amplification allowed for the listener to ignore the interfering signals, but "... a hopeless jumble resulted when listening (two ears) with only one pickup" (33, p. 611). Nevertheless,

Schowe, a hard-of-hearing individual, compared his pseudo-binaural amplification with monaural equipment and indicated at least one advantage of binaural amplification: "One blessing of my aid... , is that background noises stay where they belong" (46, p. 313).

The literature contains inconsistent information concerning the comparative value of binaural hearing aids for the different types of hearing losses. But the literature is quite explicit concerning the failure of monaural amplification to provide equally satisfactory listening for all persons with impaired hearing (7, 10, 13, 21, 25, 28,). Davis (13) and others (21, 25) agreed that an increase in the intensity of speech does not always cause a proportionate increase in speech intelligibility. Huizing and Ruentjes (28) and Cawthorne and Harvey (10) found that individuals with neural hearing loss exhibited recruitment showing a decrease in discrimination score when the intensity level of speech presentation was raised above a certain optimum level. Carhart (7) estimated that at least 20 per cent of hard of hearing adults exhibited special problems in connection with hearing aid use.

Although most of the reports concerning binaural hearing have been speculative, on its face value if binaural amplification could simulate conditions that approximate those of a normal hearing individual, the promise for the hearing aid user who could profit most by binaural listening would certainly be desirable. Hirsh (23, 25) on different occasion suggested need for a study of the effects of binaural amplification on a sizeable group of people with impaired hearing. Silverman (49) also stressed the need for information on binaural amplification with the hope of utilizing such information in the education of the deaf.

The present study was designed to investigate certain aspects of the performance of binaural, pseudo-binaural, and monaural amplification with people having conductive, mixed, and neural deafness under certain types of experimental conditions:

1. Speech Reception Thresholds
2. Discrimination Scores
3. Speech to Noise Ratios
4. Localization Scores

## EXPERIMENTAL DESIGN AND PROCEDURE

*Subjects:* This experiment included 20 normal hearing individuals* and 60 hard-of-hearing individuals. The hearing impaired individuals were selected by the following criteria:

1. age between 18 and 60 years
2. sophistication in the use of hearing aids
3. an organic hearing loss of between 40 and 70 db (mean of 500, 1,000, and 2,000 cycles) in both ears
4. sufficient comprehension of the language to respond to the standardized speech reception and intelligibility materials.

*0 db responses or better for both ears for frequencies of 250 to 8,999 cycles.

The 60 hypacusics had been diagnosed by otologists as conductive, mixed, or neural losses.

There was very little departure from the stated criteria in the selection of the subjects. Table 1 presents certain personal and historical information for the different subject groups. Table 2 contains information indicating the hearing loss for the three experimental groups.

## APPARATUS

SRT's and Discrimination Scores were collected in an acoustically treated room 9'6" x 11'4" x 6'10" high. The ambient noise level was below 24 db SPL. An Altec 604–C loudspeaker was placed 4' in front of the subject. In an adjoining room, high quality phonograph equipment, amplifiers, and a 2–db–step attenuator allowed the production of acceptable speech at levels up to 120 db SPL. An intercom was also provided. SRT's were collected using the spondees of C.I.D. Auditory Test W–1. Discrimination scores were collected using disc recordings of Lists 9–12 of the PB monosyllables, cut from specially prepared magnetic tapes in which adjustments were made on a rerecording, compensating for differences in output of an integrating voltmeter.

Speech/Noise Ratios and Localization Scores were collected in an anechoic chamber with a minimum dimension of 14'5". The walls were hung with 3 inch fiberglass blanket. Fig. 1 shows the negligible departure from the inverse square law for white noise through the room from either of two speakers to the subject.

The disposition of the four paired speakers around the subject is shown in Fig. 2. Each speaker was a 6–inch permanent magnet type mounted in a cabinet of the Helmholtz resonator type, each cabinet 14" high x 11" wide x 10" deep. Each pair of speakers was supported by a wood base with the cone of the "noise" speaker being 8 inches vertically superior to that of the "speech" speaker and approximately at ear level of the seated subject. The four speakers of each set (i.e., noise or speech) were in-phase, being electrically phased through the application of direct current and observation of the direction of cone excursion. The system of attenuators and keys made it possible for the eight speakers to be used singly or multiply through any of the possible combinations of speakers. The attenuation in all cases was continuous, readable in 1-db steps, with a range of 20 to 91 db. The SPLs obtained for any of the testing in the test chamber were those measured in the center of the testing area (87" from each of the pairs of speakers). A small pendulum was suspended from the ceiling at this central point and in testing, the subject was seated so that the pendulum was directly over the center of the head.

The power summation of the four sources of noise was measured by a General Radio Sound Level Meter Model 1551-A placed directly under the center weight. First, the attenuation of each noise source was such that exactly 60 db was measured on the Sound Level Meter. Next, with the attenuation remaining constant the noise was produced from the various combinations of speakers and found to be almost exactly at the SPL expected by logarithmic summation (i. e.,

when two speakers were turned on the SPL was 63 db, with three speakers the SPL was 64.5 db, and with all four the SPL was 66 db).

A monitor system was incorporated which took its signals from the response microphone (strapped around the neck of the subject) and from a tap in the speech amplifier system. Through this monitor, the operator could hear both the response of the subject and the recorded speech material.

## PROCEDURES

*Preliminary Testing.* Regular ascending audiometric procedures were followed in pure tone and speech testing. Pure-tone air and bone conduction thresholds of audibility were collected with a Beltone 15A audiometer. A Panacoustic SA101 speech audiometer was used for measuring the monaural SRTs and Discrimination Scores. The subjects were also evaluated for unaided SRTs and Discrimination Scores.

*Experimental Methods.* Binaural, pseudo-binaural, and monaural amplified listening were compared in each of the four parts of the experiment. In the measurement of the SRTs (Part 1) and Discrimination Scores (Part 2) monaural measurements were obtained for each ear, while for Speech/Noise Ratios (Part 3) and Localization (Part 4) only the preferred ear was used for monaural evaluation.

Two commercial transistor hearing aids matched for phase and frequency characteristics, and two commercial transistor hearing aids mounted into a glasses frame were used. The two matched transistor hearing aids were used in experimental testing and had a maximum acoustic gain of 64 db and a maximum acoustic output of 134 db. These aids were capable of providing adequate amplification for any hearing losses encountered in this study. The glasses aids were not used in experimental testing but were available for the individuals subjective evaluation.

The two aids were secured to a headstrap and approximated to the ear level of the subject. The ears were equated for all binaural listening. The subject was seated in the appropriate position and was instructed to turn on the aid of the ear normally used for amplification until it provided a comfortable loudness. A 1,000-cycle tone was attenuated to approximately 10 db above the threshold of audibility. Then the gain of the second aid was adjusted (either by the subject or by the tester) until the subject reported the tone sounded to be in the center of the head or equally loud at the two ears. The adjustment was checked by presenting spondee words at the same level. The gain adjustments of the hearing aids were not changed after the initial setting. Care was exercised at all times to avoid tiring the subject. Throughout experimentation, the testing procedures were followed for approximately 30 minutes depending upon the subject's indication of fatigue at which time he was allowed a 10-minute rest period.

Three questionnaires were devised to obtain the following information:

1. a case history questionnaire;
2. a questionnaire of one hundred statements, each allowing five response options. Each statement was concerned with some aspect of the hard of hearing subject's hearing loss, his personal and social attitudes, or his usage of amplification. The response options were "agree," "slightly agree," "don't know," "slightly disagree," and "disagree;"
3. a questionnaire designed to obtain a direct response from the subject with respect to his opinion of the different conditions of amplification used in the experiment.

*Part 1 (Speech Reception Thresbold).* In the determination of the SRT's for the different conditions of amplification, the six spondee word lists were alternated so that in no case did the subject listen to the same record more than once. The four conditions of amplification (monaural-right, monaural left, binaural, and pseudo-binaural) were evaluated in a pre-determined counterbalanced order.

A pre-trial period* allowed familiarization with the spondee words before the testing was started:

1. Subject was given an alphabetized list of the spondee words and instructed to read the words.
2. He then listened to one of the recorded lists at a comfortable loudness level and repeated the words he understood.

In each threshold measurement, initial setting of the attenuator was far enough above threshold that the subject could easily understand the first few spondee words that were presented. Then the intensity of the words was reduced in 2-db steps until he could no longer understand 50 percent of the words. SRT was determined at the lowest intensity at which the subject could repeat 50 percent of the words.

*Part 2: Discrimination Scores.* The PB word lists were presented in counterbalanced order with the order of amplification condition being the same as for the SRT testing. The SPL of PB words was always SRT + 36 db if this was comfortable to the subject. Otherwise, the level was adjusted to the most comfortable loudness. For scores of pseudo-binaural amplification the gain was always that which had been applied to the better ear and the instrument used was situated at the pinna of the better ear.

*Part 3 (Speech/Noise Ratios).* Speech/Noise Ratios of normal subjects were compared with the hard of hearing subjects under conditions of binaural amplification, while three conditions of amplification were compared (monaural, binaural, and pseudo-binaural) for the hard of hearing group. The order of testing of the three conditions was counterbalanced from one subject to the next. The monaural amplification was applied to the ear normally used for amplification. Pseudo-binaural amplification was obtained from the hearing aid used for monaural testing and the same approximation.

Ten combinations of the eight speech and noise speakers were used. Each time the Speech (W-1 records) was presented from one speaker at 70 SPL and the noise was gradually increased until the speech was no longer understandable. The

* It was previously determined that for maximum validity of SRTs, the subjects needed a pre-trial period of training. This was especially true of the neural losses. The word list (order A, B, C, D, E, or F) used in training was never repeated in experimental testing.

score obtained was the lowest SPL of noise at which the subject could not repeat 50 percent of the words.

Ten combinations of azimuth presentation of speech and noise were selected arbitrarily on the basis of exploratory study and presented in the following order:

| | *Speech* | *Noise* |
|---|---|---|
| 1. | front | front |
| 2. | front | right |
| 3. | front | back |
| 4. | front | left |
| 5. | front | front, right, back, left |
| 6. | right | front, right, back, left |
| 7. | front | right, back |
| 8. | front | left, back |
| 9. | front | back, left, front |
| 10. | front | back, front |

The listener's situation was similar to that employed by Hirsh (26). The subject was seated in the center of an area bounded by the speakers and in a chair equipped with a dental-type headrest. This headrest provided stabilization of the head when desired but also allowed freedom of movement when the head was unstabilized. The subject was seated directly under the pendulum. The following instructions were given:

> You are going to hear some words like those to which you have previously listened. Each time the voice will speak "Say the word' and then say a word for you to repeat. Repeat the one word. While you are repeating the words, noise will gradually increase. Just ignore the noise and keep repeating the words as long as you can understand them. Don't take your head away from the headrest — you may turn your head slightly if it helps you to hear better. Do you have any questions?

The subject was seated facing one of the pairs of speakers. Slight head rotation was permitted so that the listener might choose a more advantageous azimuth for the intelligibility of a masked signal.

*Part 4 (Localization).* The ability of the individual to localize white noise of 3 seconds duration was determined for binaural listening conditions for the normal hearing and for monaural, binaural, and pseudo-binaural for the hard of hearing group. For each condition there were four sets of stimuli involving positional or azimuth changes:

1. the subject facing a speaker with the head rigidly stabilized against the headrest;
2. same position but with the subject completely free to turn his head in any manner;
3. the subject facing between two speakers with the head stabilized;
4. same position but with the subject free to turn his head in any manner.

Twelve sets of scores were obtained in the Localization part of the study. Each of these sets of scores consisted of 15 directional judgments. These 15 combinations were randomized in order of presentation.

Before any experimental signals were presented, the subject was allowed a pre-trial training period. Each of the 15 stimuli (4 single sources, 6 sources presented doubly, 4 sources trebly, and 1 with all 4 sources simultaneously) were presented for identification by the subject. If the subject was not sure of the source, further instructions and pre-training was permitted. The training period was conducted with the subject unaided and noise was presented at a comfortable listening level.

At the beginning of the formal testing session, the following instructions were given to the subject:

> Now you are going to hear the same noise that you have just been locating. Each time you hear the noise it will be coming from one, two, three or all four of the speakers You may at some time hear all the different combinations. There is no way of knowing just what is going to come next. Just listen to the noise each time it is presented and then tell me where it came from. Do you have any questions?

For the Localization experiment each signal was presented at 70 SPL. The hearing aids were always mounted at ear level. For monaural reception the ear receiving amplification was that to which the individual was accustomed. For the pseudo-binaural reception this same instrument was utilized and situated similarly.

Pilot research had indicated that when the instruments were mounted on the chest, the subject could readily distinguish between front and rear sources if they were presented at the same energy level but that if the energy level of the rear stimulus was approximately 10 db higher, such distinction was unlikely. This was true for both monaural and Y cord listening. Since this learning effect very decidedly would affect the statistical results, and since intensity was not intended as a variable, instrumentation was always approximated at the pinna. Admittedly, even the head shadow would produce a certain amount of intensity effect upon Localization. Nevertheless, in this situation where under monaural and pseudo-binaural amplification the bilateral thresholds have a varying degree of asymmetry, the head effects might be considered relatively unimportant.

Before employing standardized statistical procedures in analyzing the Localization data, it was necessary to score each response. A total score was obtained for the 15 stimuli presented for each condition. The best possible total score for each condition was 60. This total score was arrived at by allowing a possible score of 4 for each of the 15 combinations of noise. The number of correct responses was summed, and from this sum the number of incorrect responses was subtracted.

*Subjective evaluations.* Upon completion of the formal testing, the subject was given an opportunity to answer certain questions concerning his comparative likes or dislikes for the different conditions of amplification. These subjective judgments were evaluated for general over-all preference, preference for clarity preference for naturalness, and preference as to the presence of noise within the instrument or within the head by a rank order preference for the three experimental listening conditions. The glasses aids were available for listening under everyday listening conditions. The tester and the subject went to nearby restaurants or other business places for a subjective evaluation of binaural or pseudo-binaural amplification under these conditions. The tester compiled a questionnaire from the subjective reactions of each subject.

## RESULTS AND DISCUSSION

*Preliminary Testing.* Table 3 presents the air and bone thresholds of audibility, SRTs, and Discrimination Scores for the experimental groups (conductive, mixed, neural) for the right and left ears. Examination of the table reveals a 3-db difference between the better and the poorer ear for the conductive group, 4 db for the mixed group, and a 2-db difference for the neural group. With respect to bone

conduction thresholds, the conductive group reveals approximately a 2-db difference, with almost no difference for the mixed group and approximately a 1-db difference for the neural group. The SRTs are consistent with pure tone audiometry. Table 4 reveals a high correlation, statistically significant at the .01 level, between air conduction and SRT for all groups. Even though Table 4 does reveal that both right and left ears are highly correlated with regard to pure tone and speech audiometry, the correlation for the left ears for the conductive group is less than for the right ear. Examination of Table 3 also indicates a higher Discrimination Score for the conductive group with the mixed group next and poorest for the neural group. These results are consistent with other research findings (15, 57, 58). Table 4 shows the correlation between pure tone and Discrimination Scores. Only one correlation coefficient is significant at the .05 level but in the opposite direction. Five of the correlations are negative. Table 4 suggests that by the use of regression equations one might be able to predict SRTs from pure tone thresholds (8, 16, 44). The problem in predicting Discrimination Scores from pure tone audiometry would appear to be much more complex.

Table 3 indicates that the means for the conductive group are approximately 6 db improved over the other groups. The conductive loss of 47 db begins to approach the limits of conductive loss as indicated by Davis (13). A difference of approximately 7 db between the conductive and the mixed groups in favor of the conductive group exists while there is a difference of less than 1 db in favor of the neural group when compared with the mixed group. The mixed and the neural groups are approximately the same with regard to pure tone thresholds of audibility.

Table 6 reveals no differences in terms of right and left ears and in groups versus the side (right and left ears). Table 7 provides the same information with regard to bone conduction thresholds. Table 8 reveals a 10.9 difference and a 10.5 difference in Discrimination Scores between the control and conductive groups. The t values for the conductive versus neural, and mixed versus neural indicate differences significant at below the .01 level. Table 8 also indicates that the conductive group performs best, the mixed next with the poorest performance by the neural group. Table 9 presents analysis of variance of the information already obtained in Table 8.

Table 10 shows analysis of variance for the most comfortable loudness of Discrimination Score testing. The procedure employed was to present the PB list at 35 db above the SRT, but when the words were too loud for the individual the intensity level was adjusted to the individual's comfortable loudness level. The means in Table 10 reveal that for the conductive group, approximately 34.31 db above SRT represents the most comfortable loudness level for the conductive group, 31.5 for the mixed group and 27.36 for the neural group. (This comfortable listening loudness for the neural group appears to be somewhat greater than often observed in clinical testing. If the hearing losses of the neural-loss subjects of this experiment had been more severe, the most comfortable loudness level might have been expected to be lower). The table also reveals that there is a significant difference at less than the .01 level of confidence between the groups, but there is no significant difference between sides and the group versus side.

## EXPERIMENTAL TESTING

*Speech Reception Threshold.* Table 11 shows the analysis of variance for the SRT. A significant difference is seen at the .01 level between the mean performances of the groups and the type of amplification. Not only were the groups different when listening but also the kind of amplification.

The mean SRT obtained for the different listening conditions shows that when the individual is listening with two hearing aids, the mean SRT is 30.07 db; when using pseudo-binaural listening conditions the mean SRT is 34.63; better monaural threshold, 33.30; and poorer threshold, 35.37 db. Analysis of variance exhibit statistically significant differences beyond the .01 level between the performance of the groups and for the different listening conditions. The SRT obtained with the two hearing aids was superior to any of the other conditions. Table 12 presents data on binaural, pseudo-binaural, and monaural types of amplification. For only one group (conductive) and only under one condition (pseudo-binaural versus binaural) was there a significant difference ( at the .01 level) between the means. Apparently for the neural and the mixed groups binaural hearing was no better than any of the other conditions.

*Discrimination Scores.* Table 13 presents analysis of variance for the Discrimination Scores. A comparison of Table 8 with Table 13 indicates that the groups did a little better under earphone conditions. Table 13 indicates a significant difference at the .01 level in performance between the groups and the type of experimental condition. A very small difference is seen for listening conditions including binaural, pseudo-binaural, and better monaural hearing. A discrimination score of 70.2 for better monaural hearing is slightly higher than either binaural or pseudo-binaural hearing. Although the analysis of variance exhibits a significant difference between the means, from a practical point of view a difference of less than 2 percent would present no problem operationally. The low score for the poorer monaural listening condition probably affects the F value for the experimental condition. This phenomenon is reflected in Table 14 where the only significant difference between the means at the .05 level occurs between better monaural and poorer monaural hearing for the three groups. Table 15 presents analysis of variance for the most comfortable loudness of Discrimination Score testing. Both the group and type means were significantly different at the .01 level.

*Speech/Noise Ratios.* Table 16 reveals a significant difference between the means of the groups and for the difference between the means of the different directional conditions. A difference at the .05 level of confidence exists for the different types of aids. None of the other conditions gives any significant difference. The conductive group performed best for the different directions and the experimental listening conditions, while the neural group performed poorest. The neural group could only continue to understand speech under the different experimental conditions at 2.46 db above the SRT while the conductive group could tolerate 8.81 db of noise above the SRT. The performance of the mixed group permitted them to understand speech at 5.76 db above the SRT. The poorest performance occurred when the noise source and the signal source were located in the same place. The best listening conditions appeared to be when the speech source

was in one place and the noise sources were in all of the speakers. Performance for the three groups was better when the noise sources were distributed. Table 16 also indicates that there is very little difference between the different listening listening conditions. Under these conditions binaural hearing is not superior to either pseudo-binaural or monaural.

Table 17 gives data on the S/N Ratios. The *t* values for the difference between S/N Ratios for the three groups indicate a significant difference at below the .01 level of confidence, while the *t* values for performance of the different types of listening conditions reveal no significant differences between binaural versus pseudo-binaural and binaural versus monaural. There is a significant difference at the .05 level between the pseudo-binaural and monaural conditions.

Table 18 presents data showing the relationship of the experimental directions and the binaural and pseudo-binaural conditions between the control and experimental groups. Nine of the 10 directional conditions are significant at below the .01 level of confidence for the control versus binaural listening of the experimental groups. The other *t* value is significant at the .05 level. The performance of the control group is superior to that of the experimental groups when binaural listening is compared. Nine of the *t* values are significant at beyond the .01 level of confidence when the control group is compared with the experimental groups under pseudo-binaural listening conditions. The other *t* value is significant at the .05 level. These values indicate that under all directional listening conditions the control group is superior to the experimental groups for both binaural and pseudo-binaural conditions.

*Localization.* Table 19 shows the performance of the control group under conditions of head stabilization and unstabilization and facing the speaker directly and facing between two speakers. Under only two conditions, facing speaker unstabilized (FSU) versus facing between speakers unstabilized (FBSU) and facing speakers stabilized (FSS) versus facing between speakers stabilized (FBSS) are the *t* values non-significant.

Analysis of the table indicates that the performance in localizing for the control group is superior when the head is unstabilized.

There is no significant difference in the performance of the conductive versus the neural groups and the neural versus the mixed groups under binaural listening conditions. The control group is superior to the experimental groups in performance (a total of FSU, FSS, FBSU, and FBSS). The performance of all groups is better when the groups are permitted to move their heads.

Table 20 presents analysis of variance indicating the performance of the experimental group under the different experimental listening conditions with head stabilized and unstabilized and under two directional conditions of facing a speaker directly and turning 45 degrees away from the speaker. The F values of 11.92, 88.33, and 21.81 showing the means between the groups under the experimental listening conditions, when the head is stabilized as compared to when the individual is permitted to move his head, are significant beyond the .01 level. Examination of the means for the groups with respect to all experimental conditions reveals that there is a very slight difference between the conductive and the neural groups but a larger difference between either the conductive and mixed groups and

neural and mixed groups. The means for the different listening conditions indicate binaural listening to be superior to either pseudo-binaural or monaural listening. Of the three conditions, pseudo-binaural provides the poorest performance in the Localization conditions. Examination of the means for stabilized and unstabilized conditions reveals a difference in favor of the unstabilized conditions. When the individuals were permitted movement of the head, the performance in Localization was superior to performance when the head was stabilized. This would suggest that freedom to move the head facilitates and expedites Localization (55,56).

Table 21 further analyzes the performance of the experimental groups. The *t* values reveal a significant difference at the .01 level for the groups under the different experimental listening conditions. For all groups, binaural listening performances were superior to pseudo-binaural and monaural; but monaural listening performance was superior to pseudo-binaural. Table 21 confirms the preceding analysis that binaural listening permits more adequate Localization of noise.

## PERSONAL EXPERIENCE QUESTIONAIRE

Table 22 presents the 100 chi square analyses of the questionaire. Of the 100 questions, only 2 (Questions 2 and 78) indicate that this distribution has a probability of less than the .01 level while 4 others (17, 84, 92, 96) show a probability at the .05 level. Table 23 presents the questions which showed significance and the answers of the experimental groups. In a statistical analysis one might expect 5 percent of the values to be significant by chance if all of the values are not significant. The questions which showed a probability at the .01 level dealt with the judgment of the users of the relative merits of the users in understanding men and women. Question 2 indicated response to the voices of men and womes when wearing a hearing aid. For the conductive group only one individual agreed with the statement while 4 others agreed slightly. The remaining 15 individuals did not know or did not agree. For the mixed group 1 agreed, 1 agreed slightly, while 18 did not know or disagreed. The response for the neural group indicated that 9 agreed with the statement, 3 agreed slightly, while only 4 slightly disagreed or disagreed. This analysis suggests that the neural group has greater difficulty in understanding women than men when wearing a hearing aid. Question 78 indicated responses to their own voices when wearing a hearing aid. Analysis of Question 78 reveals that 18 of the neural group slightly agreed or agreed with the question that their voice sounds different when wearing a hearing aid as compared with the conductive group in which 6 individuals agreed and 3 individuals slightly agreed. Eleven of the conductive group slightly disagreed or disagreed. The mixed group fluctuated in between. This analysis may suggest that the neural group requires greater adjustment in listening to their own voices when using amplification. In a similar vein, Questions 84, 92 and 96 reflect the tendency of greater adjustment problems for the neural group in wearing a hearing aid.

## PREFERENCES

Table 24 reflects the preferences. The conductive group preferred binaural listening to either pseudo-binaural or monaural listening. The *t* values for these conditions are significant at the .01 level. The *t* value is not significant for the preference between pseudo-binaural versus monaural. For the neural group the means of 1.91 for the pseudo-binaura and the mean of 1.94 for the monaural reveal very little difference with respect to preference although the mean of 1.91 would indicate a very small preference for pseudo-binaural listening as compared to monaural listening. The *t* values for the three experimental listening conditions for the mixed group reveal no significant differences. A mean of 1.93

for binaural and a mean of 1.96 for pseudo-binaural show only a slight difference, although the mean for the binaural listening conditions is smaller and consequently indicates a very small preference for binaural. Monaural listening represents the poorest preference for this group. The *t* value for the preference between monaural versus pseudo-binaural for the neural group is significant at the .05 level. The neural group preferred pseudo-binaural listening conditions to either binaural or monaural. The poorest preference for the neural group was in binaural listening conditions.

Table 25 indicates the preference of the experimental listening conditions in four preference categories: general, clarity, noise, and naturalness. The groups listed monaural as their first choice as against either binaural or pseudo-binaural listening. They selected binaural next in preference with pseudo-binaural as their last choice. In regard to clarity, binaural was first, pseudo-binaural second, and monaural last. When noise was introduced, monaural and pseudo-binaural listening conditions were preferred to binaural with no differences expressed between monaural versus pseudo-binaural. Under conditions of naturalness, binaural was preferred above pseudo-binaural or monaural while the poorest preference was for monaural listening. The table reveals that with respect to clarity and naturalness, binaural listening was preferred by the subjects. Under conditions of noise, monaural was preferred with binaural the poorest preference. In general, however, monaural was preferred to either binaural or pseudo-binaural listening. When each individual was questioned concerning preferences, many felt that even though binaural sounded clearer and more natural, the difference was not sufficiently great to offset wearing two hearing aids. Some indicated they had difficulty modulating their own voices. This comment was especially common to the neural group. The neural group also reported experiencing a greater amount of noise either in the instruments or in the head when wearing two aids. This phenomenon is consistent with reported research (1, 31, 59). An analysis of all the data would indicate that while binaural listening does embrace advantages for the neural group, it also presents many disadvantages. For the conductive group, the advantages would not appear to be so great since this group does very well with monaural listening. For the mixed group, the advantages and disadvantages are somewhat equally distributed .

Table 26 summarizes the favorable and unfavorable comments of the experimental groups of binaural and pseudo-binaural hearing aids in comparing them with their monaural listening experiences.

## SUMMARY

This project was designed to investigate certain aspects of the performance of hearing impaired individuals with conductive, mixed, and neural losses using binaural, pseudo-binaural and monaural amplification. Four measures were collected:

1. Speech Reception Thresholds (Spondees)
2. Discrimination Scores (PB Lists)
3. Speech/Noise Ratios
4. Localization scores.

The purpose of this study was to explore the comparative values of binaural, pseudo-binaural, and monaural listening for the different types of hearing impairment.

Sixty hard-of-hearing individuals who had worn hearing aids for a long time and were sophisticated in their use were selected as subjects. Twenty adult normal hearing individuals served as controls.

Subjects were tested in two sound field rooms, both having very little ambient noise and good decay characteristics. One room housed four pairs of speakers ( speech and noise) separated by 90 degrees to provide signals from different direction combinations for Speech/Noise Ratio and Localization testing.

Experimental testing included evaluation of binaural, pseudo-binaural, and monaural amplification under the different testing conditions of SRTs, Discrimination Scores, Speech/Noise Ratios, and Localization. The control group was compared with the hearing impaired groups under the experimental conditions of Speech/Noise Ratios and Localization.

For SRTs, binaural listening provided a slight lowering of the threshold as compared with the pseudo-binaural and better monaural thresholds. The binaural threshold was lower than the better monaural threshold by 3.9 db for the conductive group, 3.4 for the mixed and 2.4 for the neural. There is some variability in binaural summation, at least for those of neural loss. The greatest difference in thresholds for any of the conditions was reflected in the conductive group where the binaural SRT was 5.8 db lower than the pseudo-binaural SRT.

The Discrimination Scores were not significantly different for any of the groups for the binaural, pseudo-binaural, or monaural listening conditions when the better monaural score was used for evaluation. The most comfortable loudness of Discrimination Score testing above SRT was 34.5 db for the conductive group, 31.94 db for the mixed, and 28.52 db for the neural group.

For Speech/Noise Ratios the poorest performance occurred when the noise source and the signal source were located in the same place. There was very little difference in Speech/Noise Ratios between the different listening conditions. Under these conditions and for these groups binaural hearing was not superior to either pseudo-binaural or monaural. Under all directional listening conditions the control group was superior to the experimental groups for both binaural and pseudo-binaural conditions.

For the Localization of noise, binaural was superior to either pseudo-binaural or monaural listening. Of the three conditions, pseudo-binaural

provided the poorest performance. *When the individuals were permitted movement of the head the performance in Localization was superior to when the head was stabilized.* For all groups, binaural listening performances were superior to monaural, but monaural was superior to pseudo-binaural.

When each individual was questioned concerning preference for the three experimental listening conditions, many felt that even though binaural listening sounded clearer and more natural, the difference was not sufficiently great to offset wearing two hearing aids.

This investigation indicates that binaural listening appears to embrace advantages for all the groups. Nevertheless, for the conductive group, the advantages do not appear to be so great since they do well with monaural listening and indeed many of them prefer it. For the mixed group, the advantages and disadvantages are somewhat equally distributed and while they would appear to profit more than the conductive group, many of them also reject the use of two aids. The neural group's evaluation of binaural listening indicated that they experienced the greatest difficulty in adjusting to binaural listening. While some advantages did appear, these were counteracted by many disadvantages.

The groups in this investigation consistently preferred monaural to either binaural or pseudo-binaural listening. While the individuals in the conductive and mixed groups did obtain some improvement in performance, the improvement did not increase their social adequacy. For the individuals in the neural group who might profit most, binaural amplification aggravated their behavior by the introduction of noise. The individuals in this group had a great deal of difficulty in modulating their own voices and in understanding the speech of others. Since the testing in this investigation was conducted under novel conditions of binaural listening without any training, it might be advisable to investigate the effects of training on performance.

TABLE 1

PERSONAL INFORMATION OF THE CONTROL AND EXPERIMENTAL GROUPS

| Group | Age | | | | Sex | | Mean Years of Education | Mean Years of Hearing Loss | Mean Years of Hearing Aid Usage | Mean Number of Aids Used |
|---|---|---|---|---|---|---|---|---|---|---|
| | Range | Mean | S.D. | Median | M | F | | | | |
| Control | 21-36 | 28.25 | 4.71 | 27.50 | 11 | 9 | 16.25 | | | |
| Conductive | 28-60 | 45.15 | 7.44 | 46.83 | 6 | 14 | 12.00 | 23.10 | 7.65 | 2.20 |
| Mixed | 27-57 | 42.00 | 8.36 | 40.17 | 15 | 5 | 11.90 | 20.75 | 4.50 | 2.10 |
| Neural | 19-60 | 38.65 | 13.55 | 35.50 | 11 | 9 | 13.35 | 21.10 | 5.65 | 2.00 |
| Total hard of hearing | 19-60 | 41.93 | 10.50 | 41.14 | 32 | 28 | 12.42 | 21.10 | 5.65 | 2.00 |

TABLE 2

DATA ON THE PURE TONE AIR CONDUCTION THRESHOLDS OF AUDIBILITY (MEAN OF 500, 1000, and 2000 cps) FOR THE BETTER EAR, POORER EAR, AND DIFFERENCE BETWEEN EARS OF THE EXPERIMENTAL GROUPS

| Group | Better Ear | | Poorer Ear | | Difference Between Ears | |
|---|---|---|---|---|---|---|
| | Range | Mean | Range | Mean | Range | Mean |
| Conductive | 35.00 - 55.00 | 42.39 | 43.33 - 61.67 | 50.83 | 1.67 - 20.00 | 8.44 |
| Mixed | 35.00 - 76.67 | 49.82 | 41.67 - 76.67 | 58.71 | 0.00 - 28.33 | 8.89 |
| Neural | 36.67 - 71.67 | 50.41 | 38.33 - 76.67 | 56.49 | 0.00 - 20.00 | 6.08 |
| Total | 35.00 - 76.67 | 47.54 | 38.33 - 76.67 | 55.35 | 0.00 - 28.33 | 7.81 |

TABLE 3

AUDIOMETRIC INFORMATION (EARPHONE TESTING) ON PURE TONE AIR AND BONE TESTING AND SPEECH TESTING

| Group | Ear | Tone Thresholds of Audibility | | | | Speech Testing | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Air | | Bone | | Speech Reception Threshold | | Discrimination Score | |
| | | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. |
| Conductive | R | 49.25 | 6.31 | 7.83 | 4.22 | 48.50 | 5.50 | 84.00 | 8.32 |
| | L | 46.00 | 5.31 | 9.08 | 5.04 | 46.50 | 5.78 | 85.80 | 6.69 |
| Mixed | R | 56.30 | 12.12 | 28.92 | 12.26 | 54.00 | 11.11 | 71.80 | 13.22 |
| | L | 52.25 | 12.41 | 28.08 | 11.78 | 50.13 | 11.00 | 76.70 | 16.12 |
| Neural | R | 52.42 | 10.06 | 45.67 | 9.07 | 51.50 | 9.13 | 54.10 | 20.63 |
| | L | 54.50 | 11.49 | 46.25 | 9.37 | 53.00 | 11.11 | 48.40 | 17.31 |

TABLE 4

CORRELATIONS BETWEEN PURE TONE AIR CONDUCTION THRESHOLDS AND SPEECH RECEPTION THRESHOLDS: AND BETWEEN PURE TONE AIR CONDUCTION THRESHOLDS OF AUDIBILITY AND DISCRIMINATION SCORES

| | Group | Ear | r | $r^2$ |
|---|---|---|---|---|
| AC Thresholds Versus Speech Reception Threshold | Conductive | R | .81** | .65 |
| | | L | .67** | .45 |
| | Mixed | R | .94** | .88 |
| | | L | .93** | .87 |
| | Neural | R | .82** | .68 |
| | | L | .86** | .74 |
| AC Thresholds Versus Discrimination Score | Conductive | R | -.21 | .05 |
| | | L | -.13 | .02 |
| | Mixed | R | .09 | .01 |
| | | L | -.11 | .01 |
| | Neural | R | -.49* | .24 |
| | | L | -.33 | .11 |

*Significant at the .05 level
**Significant at the .01 level

TABLE 5

COMPARISONS AMONG GROUPS FOR PURE TONE AIR CONDUCTION THRESHOLDS OF AUDIBILITY

| | $Mean_1$ | $Mean_2$ | Diff. | t | F |
|---|---|---|---|---|---|
| $Conductive_1$ versus $neural_2$ | 47.63 | 53.46 | -5.83 | 2.93** | 3.21** |
| $Conductive_1$ versus $neural_2$ | 47.63 | 54.28 | -6.65 | 3.00** | 4.20** |
| $Neural_1$ versus $mixed_2$ | 53.46 | 54.28 | - .82 | .34 | 1.31 |

**Significant at the .01 level for t, .02 for F

TABLE 6

ANALYSIS OF VARIANCE FOR THE PURE TONE AIR CONDUCTION THRESHOLDS OF AUDIBILITY

| Source of Variance | df | SS | MS | F |
|---|---|---|---|---|
| Group (C, M, N) | 2 | 1,052.10 | 526.05 | 4.98** |
| Side (R,L) | 1 | 90.79 | 90.79 | .86 |
| G x S | 2 | 222.33 | 111.17 | 1.05 |
| Within | 114 | 12,042.51 | 105.64 | |
| Total | 119 | 13,407.73 | | |

**Significant at the .01 level

TABLE 7

ANALYSIS OF VARIANCE FOR THE PURE TONE BONE CONDUCTION THRESHOLDS OF AUDIBILITY

| Source of Variance | df | SS | MS | F |
|---|---|---|---|---|
| Group (C,M,N) | 2 | 28,171.38 | 14,085.69 | 159.84** |
| Side (R,L) | 1 | 3.35 | 3.35 | .04 |
| G x S | 2 | 22.63 | 11.32 | .13 |
| Within | 114 | 10,046.67 | 88.13 | |
| Total | 119 | 38,243.67 | | |

**Significant at the .01 level

TABLE 8

DATA ON DIFFERENCES IN DISCRIMINATION SCORES (EARPHONE TESTING) BETWEEN THE CONTROL AND THREE EXPERIMENTAL GROUPS

| Group | Ear | $Mean_1$ | $Mean_2$ | Diff | t | F |
|---|---|---|---|---|---|---|
| Control Versus Conductive | R | 94.90 | 84.00 | 10.90 | 4.96** | 3.06** |
| | L | 96.30 | 85.80 | 10.50 | 5.94** | 3.08** |
| Conductive Versus Mixed | R | 84.00 | 71.80 | 12.20 | 3.40** | 2.53* |
| | L | 85.80 | 76.70 | 9.10 | 2.27* | 5.80** |
| Conductive Versus Neural | R | 84.00 | 54.10 | 29.90 | 5.86** | 6.16** |
| | L | 85.80 | 48.40 | 37.40 | 8.78** | 6.70** |
| Mixed Versus Neural | R | 71.80 | 54.10 | 17.70 | 3.15** | 2.44* |
| | L | 76.70 | 48.40 | 28.30 | 5.21** | 1.16 |
| Control Versus Total Hard of Hearing | R | 94.90 | 69.97 | 24.93 | 5.64** | 15.99** |
| | L | 96.30 | 70.30 | 26.00 | 5.35** | 30.30** |

*Significant at the .05 level for t, .10 level for F
**Significant at the .01 level for t, .02 level for F

TABLE 9

ANALYSIS OF VARIANCE FOR THE DISCRIMINATION SCORES (EARPHONE TESTING)

| Source of Variance | df | SS | MS | F |
|---|---|---|---|---|
| Group (C,M,N) | 2 | 23,663.27 | 11,831.63 | 52.95** |
| Side (R,L) | 1 | 3.33 | 3.33 | .02 |
| G x S | 2 | 594.07 | 297.03 | 1.33 |
| Within | 114 | 25,473.20 | 223.45 | |
| Total | 119 | 49,733.87 | | |

**Significant at the .01 level

TABLE 10

ANALYSIS OF VARIANCE AND MEANS FOR THE MOST COMFORTABLE LOUDNESS (Db above SRT) OF DISCRIMINATION SCORES (EARPHONE TESTING)

| Source of Variance | df | SS | MS | F |
|---|---|---|---|---|
| Group (C,M,N) | 2 | 977.76 | 488.88 | 22.99** |
| Side (R,L) | 1 | 10.80 | 10.80 | .51 |
| G x S | 2 | 30.41 | 15.21 | .72 |
| Within | 114 | 2,424.13 | 21.26 | |
| Total | 119 | 3,443.09 | | |

Mean comfortable loudness for the groups:

Conductive group = 34.31 db
Mixed group = 31.50 db
Neural group = 27.36 db

**Significant at the .01 level

TABLE 11

ANALYSIS OF VARIANCE AND MEANS FOR SPEECH RECEPTION THRESHOLDS UNDER THREE EXPERIMENTAL LISTENING CONDITIONS IN SOUND FIELD

| Source of Variance | df | SS | MS | F |
|---|---|---|---|---|
| Group (C,M,N) | 2 | 3,371.63 | 1,685.82 | 25.92** |
| Type (Y 2 BP) | 3 | 989.78 | 329.93 | 5.07** |
| G x T | 6 | 54.37 | 9.06 | .14 |
| Within | 228 | 14,828.20 | 65.04 | |
| Total | 239 | 19,243.98 | | |

Mean Speech Reception Thresholds for the groups:

Conductive group = 28.85 db
Mixed group = 33.15 db
Neural group = 38.03 db

Mean Speech Reception Thresholds for the types of listening conditions:

Binaural aids (2) = 30.07 db
Pseudo-binaural aid (Y) = 34.63 db
Better monaural threshold (B) = 33.30 db
Poorer monaural threshold (P) = 35.37 db

**Significant at the .01 level

TABLE 12

DATA ON SPEECH RECEPTION THRESHOLDS FOR FOUR EXPERIMENTAL LISTENING CONDITIONS IN SOUND FIELD

| | Group | Unaided | Binaural | Pseudo-Binaural | Monaural (Better Threshold) | Monaural (Poorer Threshold) |
|---|---|---|---|---|---|---|
| Means | Conductive | 64.60 | 25.00 | 30.80 | 28.90 | 30.70 |
| | Mixed | 69.10 | 30.20 | 34.80 | 32.60 | 35.00 |
| | Neural | 68.70 | 35.00 | 38.30 | 38.40 | 40.40 |

| Tests of Differences | | Diff | t | F |
|---|---|---|---|---|
| Conductive Group | Pseudo-binaural versus binaural | 5.80 | 2.66* | 1.12 |
| | Pseudo-binaural versus better monaural | 1.90 | .91 | 1.38 |
| | Binaural versus better monaural | -3.90 | 1.93 | 1.23 |
| | Better monaural versus poorer monaural | -1.80 | .96 | 1.09 |
| Mixed Group | Pseudo-binaural versus binaural | 4.60 | 1.73 | 1.10 |
| | Pseudo-binaural versus better monaural | 2.20 | .79 | 1.07 |
| | Binaural versus better monaural | -2.40 | .89 | 1.18 |
| | Better monaural versus poorer monaural | -2.40 | .89 | 1.22 |
| Neural Group | Pseudo-binaural versus binaural | 3.30 | 1.17 | 1.53 |
| | Pseudo-binaural versus better monaural | - .10 | .03 | 1.15 |
| | Binaural versus better monaural | -3.40 | 1.26 | 1.33 |
| | Better monaural versus poorer monaural | -2.00 | .69 | 1.03 |

*Significant at the .05 level for t, .10 level for F

TABLE 13

ANALYSIS OF VARIANCE AND MEANS FOR THE DISCRIMINATION SCORES UNDER FOUR EXPERIMENTAL LISTENING CONDITIONS IN SOUND FIELD

| Source of Variance | df | SS | MS | F |
|---|---|---|---|---|
| Group (C,M,N) | 2 | 40,227.63 | 20,113.82 | 84.18** |
| Type (Y 2 B P) | 3 | 4,825.51 | 1,608.50 | 6.32** |
| G x T | 6 | 485.04 | 80.84 | .34 |
| Within | 228 | 54,477.40 | 238.94 | |
| Total | 239 | 100,015.58 | | |

Mean Discrimination Score for the groups:

Conductive group = 80.85 percent

Mixed group = 70.55 percent

Neural group = 49.73 percent

Mean Discrimination Score for the Experimental Conditions:

Binaural aids (2) = 68.73 percent

Pseudo-binaural aid (Y) = 69.90 percent

Better monaural Discrimination Score (B) = 70.20 percent

Poorer monaural Discrimination Score (P) = 59.33 percent

**Significant at the .01 level

TABLE 14

DATA ON DISCRIMINATION SCORES UNDER FOUR EXPERIMENTAL LISTENING CONDITIONS IN SOUND FIELD

| | Group | Unaided | Binaural | Pseudo-Binaural | Monaural (Better Score) | Monaural (Poorer Score) |
|---|---|---|---|---|---|---|
| Means | Conductive | 89.70 | 83.40 | 81.10 | 83.30 | 75.60 |
| | Mixed | 77.40 | 71.70 | 75.10 | 73.10 | 62.30 |
| | Neural | 61.20 | 51.10 | 53.50 | 54.20 | 40.10 |

| Tests of Differences | | | Diff | t | F |
|---|---|---|---|---|---|
| | Conductive Group | Pseudo-binaural versus binaural | -2.30 | .79 | 1.07 |
| | | Pseudo-binaural versus better monaural | -2.20 | .74 | 1.12 |
| | | Binaural versus better monaural | - .10 | .03 | 1.05 |
| | | Better monaural versus poorer monaural | 7.70 | 2.42* | 1.20 |
| | Mixed Group | Pseudo-binaural versus binaural | 3.40 | .85 | 1.32 |
| | | Pseudo-binaural versus better monaural | 2.00 | .47 | 1.57 |
| | | Binaural versus better monaural | -1.40 | .31 | 1.19 |
| | | Better monaural versus poorer monaural | 10.80 | 2.17* | 1.27 |
| | Neural Group | Pseudo-binaural versus binaural | 2.40 | .38 | 1.25 |
| | | Pseudo-binaural versus better monaural | - .70 | .11 | 1.27 |
| | | Binaural versus better monaural | -3.10 | .46 | 1.01 |
| | | Better monaural versus poorer monaural | 14.10 | 2.13* | 1.06 |

*Significant at the .05 level for t, .10 level for F

## TABLE 15

### ANALYSIS OF VARIANCE AND MEANS FOR THE MOST COMFORTABLE LOUDNESS OF DISCRIMINATION SCORE TESTING UNDER FIVE LISTENING CONDITIONS (FOUR EXPERIMENTAL PLUS UNAIDED) IN SOUND FIELD

| Source of Variance | df | SS | MS | F |
|---|---|---|---|---|
| Group (C,M,N) | 2 | 1,800.35 | 900.18 | 28.42** |
| Type (UY2RL) | 4 | 1,648.75 | 412.19 | 13.01** |
| G x T | 8 | 62.05 | 7.76 | .25 |
| Within | 285 | 9,028.80 | 31.68 | |
| Total | 299 | 12,539.95 | | |

Mean most comfortable loudness for the groups:

Conductive group = 34.50 db

Mixed group = 31.94 db

Neural group = 28.52 db

Mean most comfortable loudness for the listening conditions:

Unaided (U) = 27.03 db

Binaural aids (2) = 32.47 db

Pseudo-binaural aid (Y) = 33.57 db

Right ear (R) = 31.70 db

Left ear (L) = 32.50 db

**Significant at the .01 level

TABLE 16

ANALYSIS OF VARIANCE AND MEANS FOR THE SPEECH/NOISE RATIOS (DB NOISE ABOVE SPEECH AT 70 DB) UNDER TEN DIRECTIONAL CONDITIONS (See p. ) AND THREE EXPERIMENTAL LISTENING CONDITIONS IN SOUND FIELD

| Source of Variance | df | SS | MS | F |
|---|---|---|---|---|
| Group (C,M,N) | 2 | 12,122.31 | 6,061.16 | 407.63** |
| Direction | 9 | 3,422.86 | 380.32 | 25.58** |
| Type of aid | 2 | 118.92 | 59.46 | 4.00* |
| G x D | 18 | 59.67 | 3.31 | .22 |
| G x T | 4 | 44.05 | 11.01 | .74 |
| T x D | 18 | 226.99 | 12.61 | .85 |
| G x T x D | 36 | 165.41 | 4.59 | .31 |
| Residual (within) | 1,710 | 25,426.55 | 14.87 | |
| Total | 1,799 | 41,586.76 | | |

Mean Speech to Noise Ratio for the groups:

Conductive group = 8.81
Mixed group = 5.76
Neural group = 2.46

Mean Speech to Noise Ratio for the directions:

| | |
|---|---|
| Direction 1 = 2.94 | Direction 6 = 7.43 |
| Direction 2 = 4.12 | Direction 7 = 6.34 |
| Direction 3 = 4.86 | Direction 8 = 7.18 |
| Direction 4 = 5.47 | Direction 9 = 6.88 |
| Direction 5 = 6.53 | Direction 10 = 5.03 |

Mean Speech to Noise Ratio for the experimental conditions:

Binaural = 5.75
Pseudo-binaural = 5.33
Monaural = 5.95

*Significant at the .05 level

**Significant at the .01 level

TABLE 17

DATA ON SPEECH/NOISE RATIOS

| | Group | $\bar{X}$ | Listening Condition | $\bar{X}$ |
|---|---|---|---|---|
| Means | Conductive | 8.81 | Binaural | 5.75 |
| | Mixed | 2.46 | Pseudo-binaural | 5.33 |
| | Neural | 5.76 | Monaural | 5.95 |

| Speech to Noise Ratios | | | D | t | F |
|---|---|---|---|---|---|
| | Groups | Conductive versus neural | 6.35 | 24.52** | 1.20** |
| | | Conductive versus mixed | 3.05 | 12.51** | 1.06 |
| | | Neural versus mixed | 3.31 | 12.92** | 1.27** |
| | Listening Condition | Binaural versus pseudo-binaural | .42 | 1.42 | 1.92** |
| | | Binaural versus monaural | .20 | .66 | 1.14* |
| | | Pseudo-binaural versus monaural | .62 | 2.38* | 1.68** |

*Significant at the .05 level for t, .10 level for F

**Significant at the .01 level for t, .02 level for F

TABLE 18

DATA ON THE RELATIONSHIP OF THE EXPERIMENTAL DIRECTION OF SPEECH/NOISE RATIOS BETWEEN THE CONTROL GROUP AND TWO EXPERIMENTAL LISTENING CONDITIONS

| Group | Direction (see p. ) | Control (Two Ears Unaided) | Experimental Listening Condition | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Binaural | | | | Pseudo-binaural | | | |
| | | $Mean_1$ | $Mean_2$ | Diff | $\underline{t}$ | F | $Mean_2$ | Diff | $\underline{t}$ | F |
| Control Versus Total Experimental | ($D_1$) | 6.60 | 3.15 | 3.45 | 3.41** | 4.69** | 2.40 | 4.20 | 4.36** | 4.24** |
| | ($D_2$) | 11.80 | 4.98 | 6.82 | 6.03** | 4.02** | 2.87 | 8.93 | 8.89** | 3.10** |
| | ($D_3$) | 8.05 | 4.72 | 3.33 | 2.92** | 4.64** | 4.55 | 3.50 | 3.51** | 3.47** |
| | ($D_4$) | 11.05 | 5.02 | 6.48 | 5.76** | 5.43** | 6.05 | 5.45 | 6.35** | 3.02** |
| | ($D_5$) | 8.70 | 6.35 | 2.35 | 2.35* | 6.91** | 6.53 | 2.17 | 2.05* | 7.80** |
| | ($D_6$) | 13.70 | 7.55 | 6.15 | 5.71** | 1.40 | 7.35 | 6.35 | 5.97** | 1.36 |
| | ($D_7$) | 12.05 | 6.82 | 5.23 | 4.57** | 7.51** | 5.68 | 6.37 | 5.99** | 6.44** |
| | ($D_8$) | 11.95 | 6.98 | 4.97 | 4.29** | 6.44** | 6.82 | 5.13 | 4.76** | 5.51** |
| | ($D_9$) | 10.40 | 6.87 | 3.53 | 3.32** | 3.33** | 6.60 | 3.80 | 3.68** | 3.12** |
| | ($D_{10}$) | 8.35 | 5.08 | 3.27 | 3.05** | 5.34** | 4.48 | 3.87 | 4.37** | 3.55** |

*Significant at the .05 level for $\underline{t}$, .10 level for F
**Significant at the .01 level for $\underline{t}$, .02 level for F

TABLE 19

DATA ON BINAURAL LOCALIZATION OF NOISE IN SOUND FIELD BY: THE CONTROL GROUP UNDER TWO HEAD STABILIZATION AND TWO DIRECTION CONDITIONS; AND THE CONTROL GROUP VERSUS THE THREE EXPERIMENTAL GROUPS USING BINAURAL LISTENING

| | Condition (Control Group Unaided) | $\bar{X}$ | Group (Total Binaural) | $\bar{X}$ |
|---|---|---|---|---|
| Means | FSU | 44.90 | Control | 41.90 |
| | FBSU | 46.20 | Conductive | 21.63 |
| | FSS | 36.30 | Mixed | 16.50 |
| | FBSS | 40.20 | Neural | 19.93 |
| | Total unstabilized (FSU+FBSU) | 45.55 | | |
| | Total stabilized (FSS+FBSS) | 38.25 | | |

| | Group | Comparison | Diff | t | df | F | df |
|---|---|---|---|---|---|---|---|
| Tests of Differences | Control | FSU versus FBSU | -1.30 | .85 | 38 | 3.79** | 19/19 |
| | | FSU versus FSS | 8.60 | 4.89* | 38 | 5.25** | 19/19 |
| | | FSU versus FBSS | 4.70 | 2.80** | 38 | 4.68** | 19/19 |
| | | FBSU versus FSS | 9.90 | 4.68** | 38 | 1.39 | 19/19 |
| | | FBSU versus FBSS | 6.00 | 2.93** | 38 | 1.24 | 19/19 |
| | | FSS versus FBSS | -3.90 | 1.76 | 38 | 1.12 | 19/19 |
| | | FSU+FBSU versus FSS+FBSS | 7.30 | 5.32** | 78 | 2.20** | 39/39 |
| | Control (Unaided) Experimental (Binaural) | Control versus conductive | 20.28 | 13.61** | 158 | 2.51** | 79/79 |
| | | Control versus neural | 21.98 | 14.33** | 158 | 2.72** | 79/79 |
| | | Control versus mixed | 25.40 | 18.12** | 158 | 2.11** | 79/79 |
| | | Conductive versus neural | 1.70 | .93 | 158 | 1.08 | 79/79 |
| | | Conductive versus mixed | 5.13 | 3.00** | 158 | 1.29 | 79/79 |
| | | Neural versus mixed | 3.43 | 1.96 | 158 | 1.29 | 79/79 |

*Significant at the .05 level for t, .10 level for F
**Significant at the .01 level for t, .02 level for F
FSU = Facing Speaker Unstabilized
FBSU = Facing Between Speakers Unstabilized
FSS = Facing Speaker Stabilized
FBSS = Facing Between Speakers Stabilized

**TABLE 20**

ANALYSIS OF VARIANCE AND MEANS FOR THE LOCALIZATION OF NOISE IN SOUND FIELD USING THREE TYPES OF EXPERIMENTAL LISTENING CONDITIONS WITH THE HEAD STABILIZED AND UNSTABILIZED AND TWO DIRECTIONAL CONDITIONS (FACING ONE SPEAKER AND FACING BETWEEN TWO SPEAKERS)

| Source of Variance | df | SS | MS | F |
|---|---|---|---|---|
| Group (C,M,N) | 2 | 2,387.51 | 1,193.76 | 11.92** |
| Type (2 Y 1) | 2 | 17,691.01 | 8,845.51 | 88.33** |
| Stability (S,U) | 1 | 2,184.05 | 2,184.05 | 21.81** |
| Direction (FS, BS) | 1 | 235.75 | 235.75 | 2.35 |
| S x D | 1 | .45 | .45 | .01 |
| G x S | 2 | 27.23 | 13.62 | .14 |
| G x D | 2 | 145.91 | 72.96 | .73 |
| T x D | 2 | 60.81 | 30.41 | .30 |
| G x T | 4 | 814.62 | 203.66 | 2.03 |
| T x S | 2 | 587.23 | 293.62 | 2.93 |
| S x G x D | 2 | 183.64 | 91.82 | .92 |
| S x T x D | 2 | 319.64 | 159.82 | 1.60 |
| D x G x T | 4 | 291.62 | 72.91 | .73 |
| S x T x S | 4 | 571.04 | 142.76 | 1.43 |
| G x T x S x D | 4 | 51.43 | 12.86 | .13 |
| Residual within) | 684 | 68,497.50 | 100.14 | |
| Total | 719 | 94.049.44 | | |

Mean Localization Scores for the groups:

Conductive group (C) = 14.87
Mixed group (M) = 10.90
Neural group (N) = 14.65

Mean Localization Scores for experimental listening conditions:

Binaural (2) = 19.35
Pseudo-binaural (Y) = 7.23
Monaural (1) = 13.84

Mean of Localization Scores for stabilization conditions:

Stabilized (S) = 11.73
Unstabilized (U) = 15.21

*Significant at the .05 level

**Significant at the .01 level

FS = Facing Speaker
BS = Between Speakers

TABLE 21

DATA ON THE LOCALIZATION OF NOISE IN A SOUND FIELD USING THREE TYPES OF EXPERIMENTAL LISTENING CONDITIONS

| | Group | Binaural $\bar{X}$ | Pseudo-binaural $\bar{X}$ | Monaural $\bar{X}$ |
|---|---|---|---|---|
| Means | Conductive | 21.63 | 6.53 | 16.45 |
| | Mixed | 16.50 | 5.43 | 10.78 |
| | Neural | 19.93 | 9.73 | 14.30 |
| | Combined (C+M+N) | 19.35 | 7.23 | 13.84 |

| | Group | Condition | D | $t$ | df | F | df |
|---|---|---|---|---|---|---|---|
| Tests of Differences | Conductive | Binaural versus pseudo-binaural | 15.10 | 9.23** | 158 | 1.46* | 79/79 |
| | | Binaural versus monaural | 5.1[illegible] | 3.09** | 158 | 1.31 | 79/79 |
| | | Pseudo-binaural versus monaural | -9.93 | 6.54** | 158 | 1.11 | 79/79 |
| | Mixed | Binaural versus pseudo-binaural | 11.08 | 6.36** | 158 | 1.54* | 79/79 |
| | | Binaural versus monaural | 5.73 | 3.11** | 158 | 1.03 | 79/79 |
| | | Pseudo-binaural versus monaural | -5.35 | 2.96** | 158 | 1.59* | 79/79 |
| | Neural | Binaural versus pseudo-binaural | 10.20 | 7.47** | 158 | 2.03** | 79/79 |
| | | Binaural versus monaural | 5.63 | 3.48** | 158 | 1.11 | 79/79 |
| | | Pseudo-binaural versus monaural | -4.58 | 3.57** | 158 | 1.82** | 79/79 |
| | Total Experimental | Binaural versus pseudo-binaural | 12.13 | 13.13** | 478 | 1.64** | 239/239 |
| | | Binaural versus monaural | 5.51 | 5.48** | 478 | 1.11 | 239/239 |
| | | Pseudo-binaural versus monaural | -6.62 | 7.39** | 478 | 1.48** | 239/239 |

*Significant at the .05 level for $t$, .10 level for F
**Significant at the .01 level for $t$, .02 level for F

TABLE 22

QUESTIONS OF THE PERSONAL EXPERIENCE QUESTIONNAIRE FOR WHICH chi square ANALYSIS SHOWED SIGNIFICANT DIFFERENCES FOR EXPERIMENTAL GROUP RESPONSES, AND THE CATEGORICAL RESPONSES

| Questions | | |
|---|---|---|
| Number | Type of Question | Wording |
| 2 | (Aided Discrimination) | When I wear my hearing aid I have less trouble understanding men than women. |
| 17 | (Self Appraisal) | Being hard of hearing is worse than any other handicap. |
| 78 | (Problem with aids) | My voice sounds much different when I wear a hearing aid. |
| 84 | (Noise Problems) | Door slams sound very loud to a hearing aid user. |
| 92 | (Aided Discrimination) | With an aid I can hear someone talking in the next room quite well. |
| 96 | (Localization) | I can tell which door closes if I have a hearing aid. |

TABLE 22--Continued

| Experimental Groups | Categorical Responses | | | | | $\chi^2$ |
|---|---|---|---|---|---|---|
| | Agree | Slightly Agree | Don't Know | Slightly Disagree | Disagree | |
| Conductive | 1 | 4 | 6 | 1 | 8 | 21.16** |
| Mixed | 1 | 1 | 4 | 4 | 10 | |
| Neural | 9 | 3 | 4 | 4 | 2 | |
| Conductive | 0 | 1 | 0 | 3 | 16 | 16.07* |
| Mixed | 2 | 0 | 5 | 1 | 12 | |
| Neural | 0 | 3 | 1 | 2 | 14 | |
| Conductive | 6 | 3 | 0 | 2 | 9 | 30.43** |
| Mixed | 6 | 6 | 3 | 5 | 0 | |
| Neural | 12 | 6 | 2 | 0 | 0 | |
| Conductive | 10 | 3 | 1 | 1 | 5 | 18.47* |
| Mixed | 7 | 4 | 3 | 5 | 1 | |
| Neural | 10 | 8 | 2 | 0 | 0 | |
| Conductive | 7 | 9 | 0 | 3 | 1 | 18.26* |
| Mixed | 6 | 5 | 2 | 3 | 4 | |
| Neural | 1 | 7 | 4 | 0 | 8 | |
| Conductive | 10 | 1 | 0 | 6 | 3 | 19.55* |
| Mixed | 1 | 7 | 3 | 5 | 4 | |
| Neural | 2 | 5 | 2 | 5 | 6 | |

*Significant at the .05 level
**Significant at the .01 level

TABLE 23

DATA ON PREFERRED CONDITION FOR THE PREFERENCE OF THREE EXPERIMENTAL LISTENING CONDITIONS

| | Group | Type of Listening Condition | | |
|---|---|---|---|---|
| | | Binaural $\bar{X}$ | Pseudo-binaural $\bar{X}$ | Monaural $\bar{X}$ |
| Means | Conductive | 1.76 | 2.10 | 2.14 |
| | Mixed | 1.93 | 1.96 | 2.11 |
| | Neural | 2.14 | 1.91 | 1.94 |

| | Group | Condition | D | t | F | Preferred Condition |
|---|---|---|---|---|---|---|
| Tests of Differences | Conductive | Binaural versus pseudo-binaural | -.34 | 3.59** | 1.35 | Binaural |
| | | Binaural versus monaural | -.38 | 3.44** | 1.34 | Binaural |
| | | Pseudo-binaural versus monaural | -.04 | .37 | 1.81** | Pseudo-binaural |
| | Mixed | Binaural versus pseudo-binaural | -.03 | .23 | 2.00** | Binaural |
| | | Binaural versus monaural | -.18 | 1.58 | 1.14 | Binaural |
| | | Pseudo-binaural versus monaural | -.15 | 1.59 | 1.77** | Pseudo-binaural |
| | Neural | Binaural versus pseudo-binaural | .23 | 2.11* | 1.24 | Pseudo-binaural |
| | | Binaural versus monaural | .20 | 1.68 | 1.12 | Monaural |
| | | Pseudo-binaural versus monaural | -.03 | .28 | 1.39 | Pseudo-binaural |

*Significant at the .05 level for t, .10 level for F
**Significant at the .01 level for t, .02 level for F

TABLE 24

MEANS, DIFFERENCES BETWEEN THE MEANS, t AND F VALUES, AND PREFERRED CONDITION FOR THE PREFERENCE OF THREE EXPERIMENTAL LISTENING CONDITIONS IN FOUR PREFERENCE CATEGORIES BY THE TOTAL EXPERIMENTAL GROUP

| | Preference Category | Type of Listening Condition | | |
|---|---|---|---|---|
| | | Binaural $\bar{X}$ | Pseudo-binaural $\bar{X}$ | Monaural $\bar{X}$ |
| Means | General | 2.08 | 2.21 | 1.72 |
| | Clarity | 1.66 | 1.92 | 2.43 |
| | Noise | 2.30 | 1.85 | 1.85 |
| | Naturalness | 1.75 | 1.98 | 2.27 |

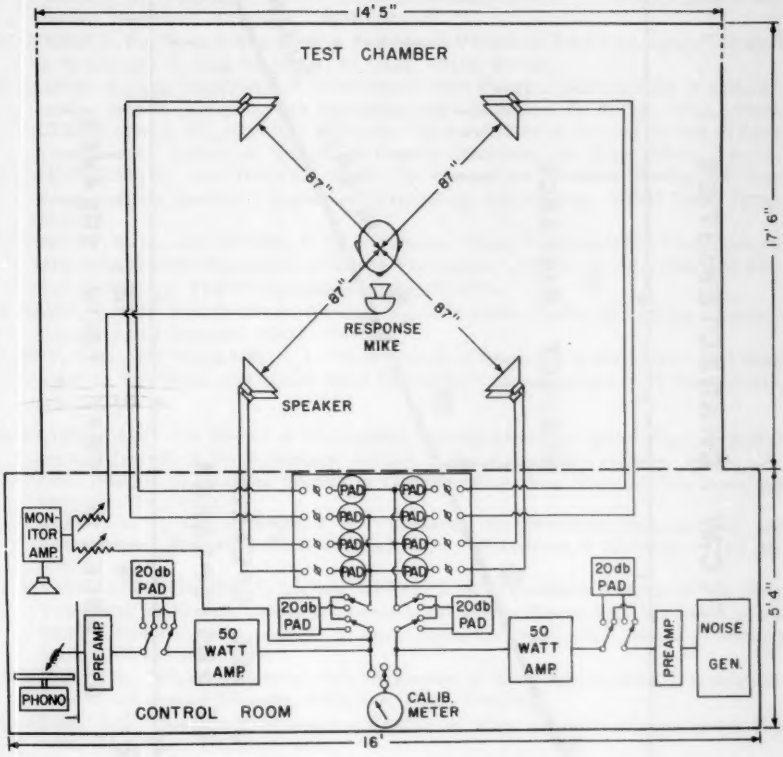
| | | Condition | D | t | F | Preferred Condition |
|---|---|---|---|---|---|---|
| Tests of Differences | General | Binaural versus pseudo-binaural | -.13 | 1.06 | 1.67* | Binaural |
| | | Binaural versus monaural | .36 | 2.38* | 1.26 | Monaural |
| | | Pseudo-binaural versus monaural | .49 | 5.21** | 2.11** | Monaural |
| | Clarity | Binaural versus pseudo-binaural | -.26 | 2.03* | 1.43 | Binaural |
| | | Binaural versus monaural | -.77 | 5.88** | 1.33 | Binaural |
| | | Pseudo-binaural versus monaural | -.51 | 4.97** | 1.08 | Pseudo-binaural |
| | Noise | Binaural versus pseudo-binaural | .45 | 5.33** | 1.62* | Pseudo-binaural |
| | | Binaural versus monaural | .45 | 5.56** | 2.04** | Monaural |
| | | Pseudo-binaural versus monaural | 0.00 | 0.00 | 1.26 | No difference |
| | Naturalness | Binaural versus pseudo-binaural | -.23 | 1.93 | 1.36 | Binaural |
| | | Binaural versus monaural | -.52 | 3.90** | 1.08 | Binaural |
| | | Pseudo-binaural versus monaural | -.29 | 2.28* | 1.47 | Pseudo-binaural |

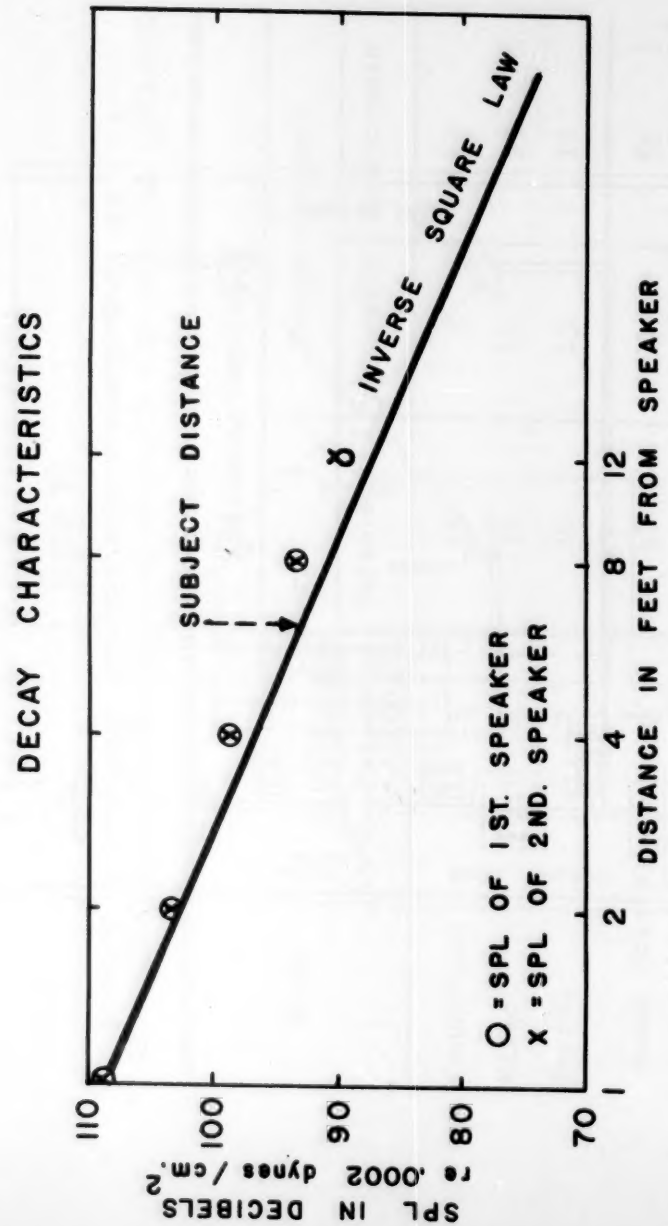
*Significant at the .05 level for t, .10 level for F
**Significant at the .01 level for t, .02 level for F

TABLE 25

SUMMARY OF FAVORABLE AND UNFAVORABLE COMMENTS ON THE BINAURAL AND PSEUDO-BINAURAL LISTENING AS COMPARED WITH MONAURAL LISTENING

| Group | Listening Condition | | | |
|---|---|---|---|---|
| | Binaural | | Pseudo-binaural | |
| | Favorable | Unfavorable | Favorable | Unfavorable |
| Conductive | 13 | 15 | 8 | 17 |
| Mixed | 12 | 14 | 10 | 19 |
| Neural | 11 | 16 | 13 | 17 |
| Total (C+M+N) | 36 | 45 | 31 | 53 |


14' 5"
TEST CHAMBER
87"
87"
87"
87"
17' 6"
RESPONSE MIKE
SPEAKER
PAD
MON-ITOR AMP.
20db PAD
20db PAD
20db PAD
20db PAD
PREAMP.
50 WATT AMP.
50 WATT AMP.
PREAMP.
NOISE GEN.
PHONO
CONTROL ROOM
CALIB. METER
5' 4"
16'


DECAY CHARACTERISTICS
SUBJECT DISTANCE
INVERSE SQUARE LAW
O = SPL OF 1ST. SPEAKER
X = SPL OF 2ND. SPEAKER
SPL IN DECIBELS re .0002 dynes / cm.2
DISTANCE IN FEET FROM SPEAKER
110
100
90
80
70
1
2
4
8
12

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# THE PROBLEM OF HEARING IN SNAKES*

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*From the Princeton Psychological Laboratory. This investigation was aided by a contract with the Office of Naval Research and by Higgins funds allotted to Princeton University. Permission is granted for reproduction and use by the U. S. Government.*

There has been little study of hearing in snakes, and many writers have expressed the opinion that they are entirely deaf, or are sensitive only to vibrations communicated to the head through the substratum. This view has arisen because these animals lack an external ear and do not make any obvious responses to sounds.

An experimental study was made by Manning (1) in 1923 on diamond-back rattlesnakes and a few other vipers. He placed them in a box that was provided with a viewing hole and exposed them to loud tones of frequencies from 43 to 2752 cycles per second, and failed in most instances to observe any startle reaction or other response to the sounds. On a few occasions the diamond-back rattlesnakes produced their characteristic rattle in response to an aerial tone of 43 cps, but failed to do so at 86 cps. A timber rattler responded to these two tones but never to higher tones. More frequent reactions were obtained from these two species when the sound was transmitted to the frame of the box in which they were kept. Manning concluded that these snakes have a defective sense of hearing. Indeed, under the conditions of this experiment the stimulation might well have been tactual rather than auditory. It must be borne in mind, however, that an absence of reaction to sounds is no proof that an animal is unable to hear.

The anatomy of the snake's ear is peculiar, and is usually regarded as degenerate (2). There is no trace of external ear, tympanic cavity, or tympanic membrane. An inner ear is present, and as usual for the reptiles it consists of three semicircular canals, utricle, saccule, lagena, and a simple cochlea. There is a columella that expands at its proximal end to form a conical stapes resting in the oval window. Its peripheral end is articulated with a flat, triangular bone lying beneath the skin and muscle layers at the side of the head. This bone is the quadrate, which has become detached from the skull and lies relatively free, secured only loosely by ligaments to the lower jaw and the dorsolateral skull wall.

These arrangements have been considered by many to be unsuitable for the reception of aerial sounds, and lend substance to the belief that the snake has little or no hearing.

The present experiments were designed to explore further the possibilities of sound reception in the snake's ear through the use of cochlear potentials.

## PROCEDURE

The observations were made on several species of nonpoisonous snakes of the family Colubridae. Included were 5 pine snakes (*Pituophis m. melanoleucus* Daudin), 5 garter snakes (*Thamnophis s. sirtalis* L.), 1 ribbon snake (*Thamnophis s. sauritus* L.), 5 common water snakes (*Natrix s. sipedon* L.), and 2 Florida water snakes (*Natrix sipedon pictiventris* Cope). The pine snakes were 5 to 6 feet in length and the others were 3 to 4 feet in length, except for 2 of the common water snakes that were only a few weeks old and measured 7 to 8 inches.

All were anesthetized with 20 per cent Urethane (ethyl carbamate) at a dosage rate of 6 cc per kg of body weight.

For the recording of electrical potentials a hole was drilled into the dorsal wall of the otic capsule, and an electrode in the form of a steel needle was inserted so as to make contact with the perilymph of the superior portion of the labyrinth. The needle was insulated except at its tip, and was fitted tightly in the drill hole to prevent loss of fluid. Usually the needle entered the superior semicircular canal, but sometimes it was pushed farther into the utricle without any notable alteration in the results. An indifferent electrode was located in other tissues near by, usually being inserted beneath the skin in the cranial region.

For stimulation with aerial sounds the snake's head was placed in front of a sound tube with its longitudinal axis at right angles to the tube and the lateral surface 2.5 cm from the end of the tube. Sound pressure measurements were made with a probe tube and condenser microphone placed at this same location.

For vibratory stimulation a bone-conduction receiver was used, consisting of a laminated Rochelle salt crystal in a metal case, with a plastic prod extending from the moving end of the crystal through a hole in the case.

## RESULTS

Some of the results obtained with aerial sounds are presented in Fig. 1. These curves give the sound pressure in decibels relative to 1 dyne per sq cm required to produce a potential of 0.1 microvolts. The curves all show a region of greatest sensitivity between 100 and 500 cps, and then poorer sensitivity for lower and especially for higher tones.

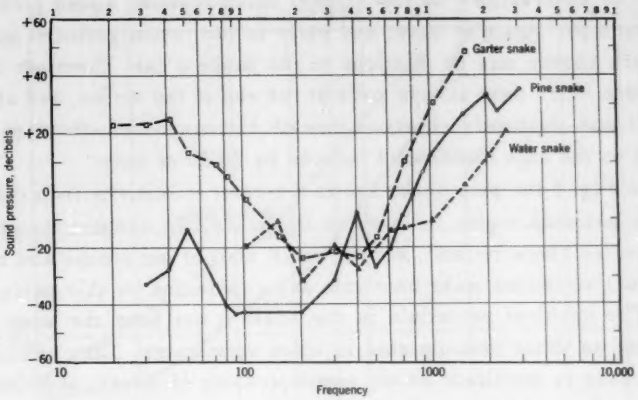


Fig. 1. Sensitivity curves for individual ears representing three species of snakes. Each curve shows at various frequencies the sound pressure in decibels relative to 1 dyne per sq cm required for a cochlear potential of 0.1 microvolts.

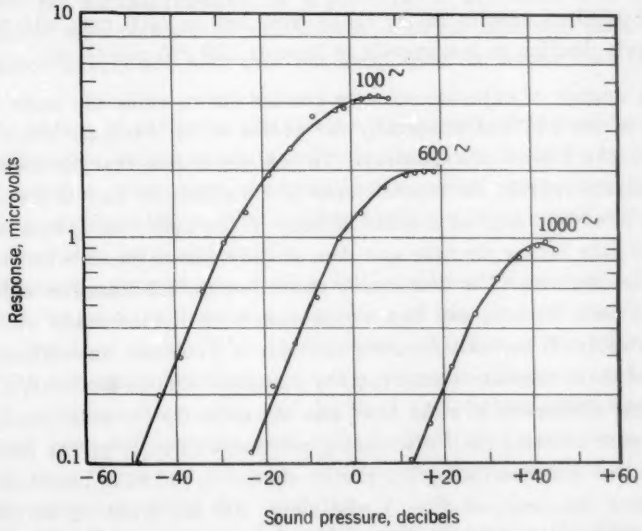


Fig. 2. Intensity functions for the ear of a pine snake. The sound pressure is in decibels relative to 1 dyne per sq cm.

The observations on the highest tones required sound pressures of 100 dynes per sq cm or more, and early in the investigation it was found that such sounds may be injurious to the snake's ear. Therefore the tests with these tones were always made at the end of the series, and after such tests it was frequently observed that all the responses—those to the low as well as the high tones—were reduced by 20 db or more.

In Fig. 1 the pine snake shows a greater sensitivity than the others, and its maximum region is lower in frequency. We suspect that this is a true species characteristic, but the small size of our groups and the large individual variations make uncertain any conclusion on this point.

The cochlear potentials in the snake's ear have the same general character as those demonstrated in other vertebrates. They exhibit a linear increase in magnitude as the sound pressure is raised, and then depart from this form as the sound reaches high levels, passing through a maximum and declining as shown in Fig. 2.

The maximum values reached are greater for the lower tones of the snake's range than for the higher, just as has been found for many other animals. As shown, the maximum for 100 cps was 4.3 microvolts, whereas for 1000 cps it was just under 1 microvolt. These maximums may be compared with those obtained in the cat, which attain a fairly uniform magnitude of 1000 microvolts in the range from 100 to 2000 cps, and then progressively decline to 1 microvolt or less at 100,000 cps (3, 4).

A number of experiments were carried out to study the mode of stimulation of the ear, and especially the action of the quadrate bone.

1. *The Vibration Hypothesis.* To test the notion that the snake's ear is stimulated only by the transmission of vibrations by way of the substratum the head was laid on a table in front of the sound tube, first with the operated side facing the tube and then at the same distance with this side away from the tube. The sound tube came through the massive wall of the shielded room without any firm connection with it, and made no contact with the table. If the sound waves first set in vibration the surface of the table and these vibrations were thereby communicated to the head, it should make little difference how the head was oriented. On the other hand, if the sounds were exerting their alternating pressures directly on the tissues of the head, the location facing the source should be the more favorable. This was indeed the case, as Fig. 3 will show. For all tones up to 1500 cps the averted position gave significantly poorer responses, and for 2000 cps this position no longer gave measurable potentials.

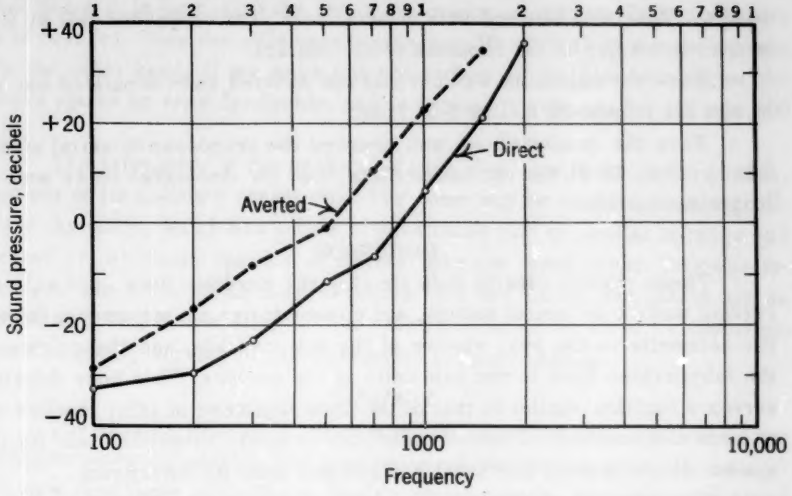


Fig. 3. The curves represent the sound pressure (in decibels relative to 1 dyne per sq cm) required for a potential of 0.1 microvolts in a pine snake under two conditions of stimulation, with the observed ear facing the sound tube (direct) and with this ear away from the sound tube (averted).

2. *Nature of Vibratory Stimulation.* Responses were readily obtained when vibrations were communicated directly to the head by means of a crystal vibrator. They were observed in the animal represented in Fig. 3 over the range from 100 to 2000 cps but could not be obtained at 3000 cps, just as was true for aerial sounds.

Various points of application of the vibrator were tried. The most favorable location was over the midportion of the quadrate bone. Also effective, but less so by 10 to 15 db, were positions at the edges of this bone. The responses declined noticeably when the vibrator was moved just away from the quadrate bone, and declined still further when more remote locations over soft tissues were tested. Good responses were obtained from all bony regions of the head, such as the dorsal surface of the skull and the posterior part of the lower jaw.

3. *The Transmission of Aerial Sounds.* Removing the skin over the quadrate bone, and also some of the muscle layers, had little or no effect on either vibratory or aerial stimulation. Cutting the ligamentary attachments of the quadrate to the lower jaw and to the squamous bone had little effect also.

During aerial stimulation, the responses were observed while the quadrate bone was touched with a metal prod. The responses fell by 8 db or more according to the firmness of the contact.

When the columella was cut and the severed ends separated but left in situ the responses fell by 6 or 7 db.

When the quadrate bone was removed the responses to aerial sounds fell by 10 to 18 db for the lower tones, and for the higher tones were no longer measurable.

## DISCUSSION

These results clearly indicate that the quadrate bone acts as a receiving surface for aerial sounds, and communicates its movements through the columella to the oval window of the otic capsule, and thence through the labyrinthine fluid to the hair cells of the cochlea. This bone therefore serves a function similar to that of the drum membrane of other reptiles and of birds and mammals. Evidently this bone is freely suspended, and its ligaments do not impose any notable restraints upon its movements.

The removal of the quadrate bone produces a marked reduction in sound transmission, but not as great a reduction as destruction of the drum membrane does in the higher animals. For example, the total removal of the drum surface in the cat reduces the responses to low tones by 40 to 45 db (5). This great loss occurs because the ossicular chain lies relatively free in the middle ear cavity and itself presents only small surfaces for the sound to act upon. Also, when the mechanical advantage afforded by the large drum surface is lost the sounds can act almost equally well on the two cochlear windows, the round and oval windows, and these two pressures tend to cancel one another in their actions on the cochlear fluids.

In the snake, the loss in transmission is relatively slight when the columella is broken because various soft tissues remain to connect the quadrate with the stapes in the oval window. The loss is only moderately large when the quadrate bone is removed because the muscle and fiber layers over the stapes continue to transmit sound pressures to it. There may be some cancellation effect from the action of sounds on a channel that serves as a release path analogous to the round window of higher forms, but this channel is covered by a tough fibrous layer that probably protects it from this action to some extent.

The responses of the snake to sounds are limited to the low-frequency range, but within this range the sensitivity is reasonably good. It is inferior to that of the cat if we compare the snake in the region of 100 to 500

cps where it is best with the cat in the region of 2000 to 7000 cps where it is best (6). Then the difference amounts to 10 to 20 db in the cat's favor. On the other hand, if we make the comparison in the low-tone region the snake shows up more creditably, and is superior to the cat for 100 and 200 cps.

The inferiority of the snake's hearing thus lies in its limited range, and not in its absolute sensitivity. The same may be said for its close relative the turtle, which has a form of sensitivity that is similar in range and degree (7, 8). Some species of turtles, like the wood turtle *Clemmys insculpta*, are 10 to 20 db more sensitive than the snake, but others are on the same level. The hearing in these reptiles doubtless serves a useful purpose in giving warning of the movements of large animals.

## SUMMARY

The hearing of some common species of snakes was studied by the cochlear potential method. The results do not support the generally accepted view that these animals are deaf to aerial sounds, but indicate instead a narrow limitation in range. For the low tones between 100 and 700 cps the snakes are moderately sensitive both by air and bone conduction. In this low range the absence of an external ear and the use of the quadrate bone instead of a tympanic membrane as a sound receiving surface is not a serious handicap.

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# NYSTAGMUS AUDIOCINÉTIQUE

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## ABSTRACT

A rotating sound field preferably composed of white noise or a series of clicks obtainable by simple and technical means, provokes kinetic reactions: nystagmus, balancing movements of the head, etc. These phenomena recall the physiological problems of audition and equilibrium. They can be utilized in practice as a means of objective audiometry and in particular in the usual case of auditory tracking.

An audiokinetic nystagmus exists just as there exists an optokinetic nystagmus, an olfactokinetic nystagmus, a psychokinetic nystagmus. It can be defined by making this observation: a turning sound source around a subject releases a nystagmus in the subject. By analogy to these different kinetic reactions, the optokinetic reaction being best known, we have given to this communication the title audiokinetic nystagmus, but the reactions of a subject exposed to a turning sound source are not limited solely to nystagmus. There exist other reactions which seem interesting to us to describe.

If one submits a subject to a turning sound field around him, one can ascertain constant reactions in the same measure as there exists an auditory function. These are all reactions which are well known in vestibular tests: nystagmus, the Romberg sign, deviation of the limbs, vegetative reactions.

## NYSTAGMUS

Visual correction inhibits the reaction when the eyes are open. A direct examination of the movements of the eyes in infrared light or by nystagmography shows us identical movements to those obtained by an optokinetic reaction: there exists a slow phase parallel to the displacement of the sound source, corrected by a rapid phase. This nystagmus cannot be overcome by the will of the subject or by learning. When one tries to fix the eyes, one succeeds during the very short time corresponding to two or three complete rotations of the sound source. After a time it produces an irrestible return of the audiokinetic nystagmus. This return is followed by an amplitude of a slow phase greater than that which had preceded the voluntary inhibition. After several jerks it returns to a normal amplitude.

THE ROMBERG SIGN

The deviation of the subject's head held upright, feet together, the eyes closed, is produced by a balancing of the head which is most apparent if the rhythm of the rotation of the sound source is in the neighborhood of one turn every 3 or 3½ seconds, a time which corresponds with the natural rhythm of balancing the head in the upright position. The experiment is simple: the subject is required to take the upright position, and relax with the eyes closed. Submitted then to a turning sound source, he manifests very apparent movements of balancing as soon as the intensity of the source is 10-decibels above his threshold.

DEVIATION OF THE LIMBS

The deviation of the arms held forward is revealed in a turning sound field either in a sitting or standing position. This is followed by oscillation in the horizontal plane.

DEVIATION OF VERTICAL WRITING (Test of Japanese writing)

If one requires the writing of little signs (crosses, circles), the one below the other, the patient having his eyes closed, the written signs will be soon disposed in an undulating verticle column.

VEGETATIVE REACTIONS

In certain sensitive individuals, the experiment of the turning sound field provokes, after a certain time, reactions of nausea and discomfort. We have not investigated modifications of pulse, other heart activity, etc.

SOUND SOURCE

One can arrange a turning sound field in many ways. Theoretically the most simple, but also the most difficult to realize technically, is to dispose a loud speaker fixed on a turning arm around the center, corresponding to the head of the patient in the experiment. One arranges thus a real sound source.

The utilization of sterophonic sound reproduction permits one to create a virtual sound source. By means of magnetic recording in two channels, it is possible to create the illusion of a sound field which gives us in our experiments constant results. This method permits the use of earphones rather than of loudspeakers. The recording of the sound is made by means of two microphones incorporated into a model of the human head in order to realize the closest conditions to reality. The turning effect can be obtained by actually turning a sound source around this artificial head, but it is simpler to turn this head on itself in front of a fixed sound source.

Finally, the studies which other authors and ourselves had done on

the physiology of the sterophonic sensation, have shown that a delay of 1/1000 of a second of time of arrival of the sound in one ear with respect to the other gives the illusion of a displacement of localization of about 90 degrees.

The same effect is created if there exists a difference of 8 decibels between the sound intensities which strike each ear. The utilization of variable intensity differences of 8 to 10 decibels permits one to create a turning sound field without having appealed to the cumbersome and costly apparatus (tape recorder with two channels or a double magnetaphone with a variable delay line, etc.). It suffices, indeed, to connect on the one hand the two fixed extremities of a potentiometer, using an audiometer for example, and to connect on the other hand two earphones to that potentiometer in the following fashion: one common wire to the mobile contact of the potentiometer and two other wires independently to each earphone at the fixed extremities of the potentiometer. It would be necessary to control the extent of the mobile contact of the potentiometer so that it should not pass the variation of 8 decibels.

Finally, a turning sound source is obtained very simply by utilizing apparatus for the so-called "loudness balance test" which is now furnished for the most part in commercial audiometers.

## THE QUALITY OF THE SOUND TO BE UTILIZED

Continuous pure tones in a turning sound field give the least well-marked sensations of kinetic reactions. It is altogether different if the pure tones are interrupted by a frequency as rapid as 4 to 5 percent. White noise gives the very best responses even if it is not interrupted. Finally, the audiokinetic reactions are slow and constant in response to the emission of a series of clicks emitted at a rapid frequency. Complex sounds such as music and different noises are equally utilizable.

## CONCLUSION

A patient submitted to a turning sound source shows reactions which we have called audiokinetic: nystagmus, head movements, etc. These manifestations bear upon the discussion of the physiology of binaural audition on the one hand and on problems already as complicated as equilibration and vertigo.

These phenomenon have also a practical value in audiology which seems to us important. They are indeed utilizable as objective tests of audiometry. They can aid the uncovering of a case of malingering or simulation; but it is in child audiometry that these audiokinetic reactions can

render an important and novel contribution. They permit one to evoke oscillations of the head and of the direction of eye movements in the very young infant. They give the possibility of making an objective audiometric test of groups of infants and even of adults.

The experiment is done in the following manner: the children are grouped and disposed in a large hall, on their feet, their eyes closed, faces to the examiner. The turning sound field is furnished by two loud speakers placed on the one hand and on the other. The sound intensity is increased progressively and one notes the beginning of turning of head movements of each child as a function of intensity.

# INTENSITY DISCRIMINATION FOR NARROW BANDWIDTHS OF NOISE AT VARIOUS PULSE LENGTHS

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## ABSTRACT

Signals which had perceptually identical envelopes yielded identical Δ I's when the bandwidth of the noise was 8-cps, 32-cps, or a pure tone and when the duration of the pulse length was 32, 128, and 2048 ms. A pulse length of 512 ms yielded a different Δ I. The Δ I is primarily dependent upon the envelope characteristics of the stimulus and not upon the frequency of the stimulus except when the frequency affects the envelope characteristics. As band width increases up to 8 cps Δ I significantly decreases. As pulse length is reduced Δ I differences for the four bandwidths (.5, 2, 8, 32 cps) were eliminated. An envelope detector model is suggested to account for intensity discrimination.

## INTRODUCTION

In a previous paper (1), frequency DLs (difference limens) were determined for a wide range of noise bandwidths. For bandwidths greater than 8 cps a linear relation was found (2, 3) to describe the manner in which the frequency DL varied with bandwidth. This relation was

$$\Delta F = (\Delta I)(BW)/K$$

where

$\Delta F$ is the frequency DL
BW is the effective bandwidth of the noise stimulus
$\Delta I$ is the intensity DL.

This equation shows that $\Delta F$ is also dependent upon the ability of the auditory system to discriminate differences in intensity.

In the previous study it was found that for bandwidths below 8 cps, the relation between $\Delta F$ and bandwidth ceased to be linear, and $\Delta F$ rose as bandwidth was made more narrow. This was taken as presumptive evidence that intensity discrimination had deteriorated. It was suggested that $\Delta I$ increased because fluctuations in the envelope of noise of narrow bandwidth were perceptible. These perceptible variations caused an uncertainty in judgment of intensity differences, thus causing the threshold to rise.

This particular formulation leads to the hypothesis that the auditory system acts as an envelope detector (4).

Given this model, when the rate of envelope fluctuation is higher than the integrating time of the system, all such stimuli will be smoothed, and intensity-wise will be discriminated equally well. Therefore, it is reasonable to hypothesize that $\Delta I$ should be the same for all bandwidths of noise greater than 8 cps. Furthermore, the noise DLs should be the same as a pure tone DL at the same center frequency. Thus, a corollary hypothesis is that intensity discrimination among these stimuli is independent of their spectrum except insofar as they determine the envelope characteristics.

For very narrow bands of noise a different situation should exist. Here changes in the envelope occur so slowly that the fluctuations are perceptible. The problem is how does a listener arrive at an estimate of loudness of that pulse? In these experiments the listener will hear two such pulses and he must estimate the loudness of each and then make a comparison between them. This estimating process should reduce the accuracy of discrimination. This, then, leads to an hypothesis that for pulses in which envelope fluctuations are perceptible, $\Delta I$ will rise relative to the wider bandwidths. Furthermore, if the final intensity discrimination in the model is a statistical decision operation, the DL should rise as the bandwidth is narrowed still further. This is because the reliability of the estimate of the mean intensity varies inversely with the bandwidth pulse length product. This, of course, will apply only in the case where stimulus duration is sufficient to allow envelope fluctuation.

When the stimulus pulse length is reduced in these narrow bandwidth cases, there will be insufficient time for envelope fluctuations to occur, and the uncertainty in the intensity of the stimulus will be eliminated. Under these conditions, differences in the DL between bandwidths wider than 8 cps and those narrower will also be eliminated. Thus, a third hypothesis is that elimination of perceptible envelope fluctuations by pulse length reduction should eliminate differences in $\Delta I$ among bandwidths.

The purpose, then, of the present experiments is to examine the effects of stimuli with varying envelope characteristics on intensity discrimination. Four pulse lengths will be used: 32, 128, 512, and 2048 ms. Four bandwidths of noise with a center frequency at 800 cps will be employed: 0.5, 2, 8, and 32 cps. Thresholds will also be obtained for an 800-cps sine wave at the same pulse lengths. The research should clarify certain of the temporal properties of intensity discrimination. Further, the research should shed more light on the interrelation between frequency and intensity. Fi-

nally, it should demonstrate the utility of complex envelopes as a tool in auditory research.

## APPARATUS

Apparatus for the experiment consisted of 3 parts. First was acoustic components for generating and controlling the noise stimuli. Second was a timing and switching system. Third was a computer to measure and store the db differences in energy between pairs of stimuli. Figure 1 is a block diagram of the whole system.

In order to obtain the various bands of noise a wide band of noise fed a single-tuned circuit of variable bandwidth with a center frequency at 800 cps. This bandwidth was defined by the half-power points. A resistor type noise source was used which had a flat spectrum from 20 cps to 20 kc. This wide-band noise was filtered through a bandpass filter to obtain a 400-cps band before passing into the narrow-band filter. This procedure reduced the losses from filtering through the single-tuned circuit and also reduced the leakage of wide-band components across the narrow-band filter.

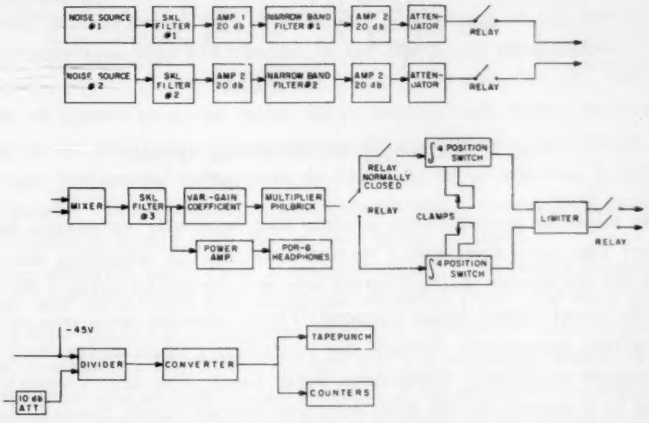


Fig. 1 The stimulus generation and measurement system

Timing was accomplished using a series of pulse operated relays (Burroughs Model 1801). These were modified such that an output pulse occurred at the end of a relay closure. This pulse was sufficient to energize the next unit. By connecting them sequentially, a cycle could be set up to repeat continuously until externally interrupted. The duration of re-

lay operation could be adjusted to within 0.1% of any desired time. These durations drifted less than 0.5% over a 2-hour period. Figure 2 shows the timing cycle employed in the experiment, along with the associated switching functions.

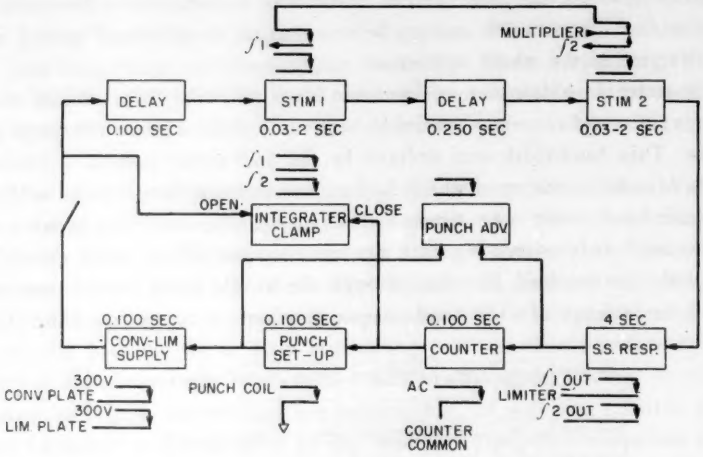


Fig. 2 The timing and switching system

The stimulus measurement system was basically an energy measuring device. The input coefficient was an amplifier for adjusting the signal level into the multiplier. Multiplication was accomplished using a Philbrick MU/DV, the input signal being squared. These squares were integrated by the appropriate integrators through the switching circuit shown in Figs. 1 and 2. Chopper stabilized integrators were used. The time constant was adjustable in 5 steps: 10, 30, 100, 200, and 500 ms. Drift, leakage losses, and all other errors in the integrators were small, the total being of the order of 50 mv maximum, or 0.1% full scale. Integrator 1 output served as reference and operated into the denominator of the divider. The divider was another Philbrick MU/DV. Since the divider could not operate with zero input, -45 v dc was applied at all times when there was no input from the integrators. Also, instability and zero drift increased greatly when the denominator voltage was less than 5 v; and above 45 v, accuracy of division decreased. Therefore a limiter was placed ahead of the divider which opened or closed the paths to both numerator and denominator if the latter was less than 5 v or greater than 45 v. In this way the divider operated over its

most accurate range, without becoming unstable or overloading.

Since the ratios appearing at the output of the divider over a run formed a continuous distribution, it was decided that a frequency distribution of the db differences between the stimuli would be constructed and the class midpoints taken as the definition of the difference between the two stimuli. This analysis was made by an analog-to-digital converter which was a set of 7 relays, each operated through a thyratron. In order to obtain the difference between stimuli in db, the firing points for each stage were adjusted in a logarithmic relation to the output of the divider. In this manner, the class midpoints of a distribution of db differences were coded on punched tape and also on counters.

Errors occurring in this measurement system were complex and numerous. Drift in analog components is unavoidable, and its effect is not simply additive. Errors in both multiplier and divider are not equal over their whole dynamic range. They were higher at both low and high input voltages. Both short and long term fluctuations in pulse length cause errors in integration. Fluctuations in the firing points of the converter thyratrons lead to instability of class limits. Variations in the power supply voltage cause considerable change in the operating characteristics of all components, especially the multiplier and the divider. Finally, the characteristics of Gaussian noise itself incur unavoidable errors such as peak clipping in the multiplier. Accuracy of the components separately and together was determined using both dc and sine-wave signals. It was found that by careful and consistent calibration accuracy, over a 6-db range could be maintained to within 0.25 db for sine waves at least.

The subjects made their responses using a key which caused a hole to be punched on the tape containing the stimulus code. The only responses punched were those for a judgment of louder. Alternate lines of the punched tape contained a stimulus code and the S's response, which in the latter case meant one of eight holes for each S. By using a tape reader it was possible to sort the responses of each S in terms of the stimulus difference presented.

## PROCEDURE

The Ss were placed in a sound isolated room, and listened through PDR-8 headphones. The average sound pressure level of the stimuli was 65 db re 0.0002 dyne/cm$^2$. Two signals were presented sequentially, separated by 250 ms. The S's task was to judge whether the second of the pair was louder or softer than the first. Thus, the method of constant stimulus differences was used. Each S had 2 response keys. That for a judgment of

louder caused a hole to be punched on the tape. The other, for a judgment of softer, was a dummy. It was found in some earlier research that without a second response category a considerable bias in threshold occurred and the addition of the dummy key eliminated it. A run consisted of 100 or 150 judgments, the former for the two longer pulse lengths and the latter for the two shorter pulse lengths. A short break was given in the middle of each run, and 10-minute rests were given between runs. Runs of the same condition were repeated until the number of observations for each stimulus category exceeded 30.

Four bandwidths and four pulse lengths were chosen, so that their products represent the maximum number of periods of the envelope expected for an ideal rectangular band of noise. On the average, the mean number of periods should be less than this product but linearly related to it. In the practical case of noise obtained from a normal resonant filter, the mean number of periods should be somewhat higher than the ideal band of noise. This is because there is not a sharp cutoff, and energy is passed at frequencies higher than or lower than that defined by the half-power points. Envelopes of 2-sec pulses with noise bandwidths of 0.5, 2, and 8 cps were examined with an oscilloscope. It was found that the average number of periods was just slightly less than the number predicted by the product of bandwidth and pulse length. The best estimate was that the number of periods was 0.87 times the product of bandwidth and pulse length.

As has been shown by Rice (5), the energy variance in a noise pulse is a function of the bandwidth and pulse length product and varies inversely with it. For products less than unity, the variance was so large that over the ±3-db range used, the distribution of differences was uniform. All the db differences occurred equally often, thus no manipulation of the signal level was required. For products greater than unity, however, the variance of the db differences decreased rapidly. In these cases it did become necessary to vary the attenuation in one channel to obtain an equal number of stimuli in each class of db differences.

The presentation of each of the 16 conditions was randomized according to a pair of orthogonal latin squares. In this manner each combination of bandwidth and pulse length preceded and followed every other combination an equal number of times. As was stated previously 100 or 150 pairs of stimuli were presented in a run. However, the total number of stimulus differences that fell within the ±3-db range of the measurement system varied as a function of the bandwidth and pulse length product. When this product became very small, the percentages of the differences lying within the range of interest decreased. For the lowest products only about

50 of the 150 differences between pulses fell in this range. For these conditions, each stimulus difference category contained an average of 8 observations. This required a repetition of 4 runs to obtain a minimum of 30 observations for each of the 6 stimulus differences. The data for these 4 separate runs were ultimately pooled, and a single threshold was determined from these pooled runs. In addition, the same combination was repeated at other times as determined by the latin square order. At least 3 replications were made for every combination of bandwidth and pulse length. Pure tone thresholds were obtained separately, but the same procedure was followed.

Analysis of the punched tapes was done using a tape reader. The number of responses per stimulus for each S was tallied on a counter. From these frequencies and the number of times the stimulus differences was presented, the proportion of louder judgments for each of the six stimulus differences was determined. The proportions were plotted on probability paper and then fitted by eye. The thresholds were defined as the probable error of the fitted distributions.

Seven Ss were used, 6 females (A, B, C, D, F, and G) and 1 male (E). All were between the ages of 30 and 40 and had normal audiograms as well as no known systemic anomalies. All but one of the Ss were experienced listeners at the outset. However, none were very proficient at discriminations with noise, so that 4 weeks were used as training. By the end of that time, the performance of all Ss was stable.

## RESULTS

One consistent finding in all of the present experiments was the substantial and significant differences in threshold between Ss. These systematic differences make averaging over the Ss unwarranted, for any such pooling would be misleading. Therefore, each listener was treated independently in the analyses of the results.

Not only were significant differences observed among the Ss, but considerable variation was observed within individual Ss from trial to trial. At least 3 independent threshold determinations were made for each condition and over half of the conditions were repeated 4 times. The average difference among the separate determinations varied between 0.25 and 1.0 db for the individual Ss. The extent of variation depended upon the threshold magnitude and upon the individual S. The differences among separate determinations for the short pulse lengths were generally larger than for the longer pulse lengths. Those Ss who reported most uncertainty about their method of discrimination yielded generally higher thresholds over all

conditions and yielded lower reliability scores. In general, the difference among repeated measurements was approximately 25% of the average threshold.

Thresholds for the shorter pulse lengths, independent of bandwidths, are somewhat biased. In a fraction of the runs it was not possible to derive a threshold, since the discrimination probability for all the stimulus differences was approximately at chance level. Limitations in the measurement system precluded an increase in the size of the class intervals sufficient to obtain satisfactory transition curves. It was necessary, to discard 33% of runs for the two shorter pulse lengths and only 5% for the two longest pulse lengths. It may be noted that 70% of these discarded thresholds were contributed by only 3 of the Ss. These Ss, in turn, demonstrated the highest thresholds over all conditions. The result of this selection process is that thresholds for a fraction of the subjects are biased low. The magnitude of the bias was indeterminate.

Shown in Table 1 and Fig. 3 are the average intensity DLs over all stimulus conditions for each of the 7 Ss. Composite curves of bandwidth vs pulse length are shown in Fig. 4, in which the points are the average threshold of each S. The curves in Fig. 4 were constructed by eye and represent essentially the means of the array at each pulse length. These curves should be treated as merely descriptive, for they have been constructed by pooling data for Ss who differ significantly among themsleves.

From Figs. 3 and 4 it may be seen that the threshold decreases exponentially with pulse length for the 32-cps bandwidth and the pure tone. This result is consistent with that found by Garner and Miller (6). The 8-cps-bandwidth data appears to exhibit a somewhat higher threshold than the 32-cps-bandwidth, at the intermediate pulse lengths especially. At the longest pulse length, the threshold for the 8-cps-bandwidth appears to converge on the threshold for the 32-cps-bandwidth and the pure tone. This may be seen most clearly in Fig. 3. The function for the 2-cps-bandwidth and the 0.5-cps-bandwidth are quite different from the other three functions. In general, thresholds for the 2-cps-bandwidth seemed to be less affected by pulse length than the rest. For example, the DL for the 2-cps-bandwidth changed by a factor 1.8 when pulse length increased from 32 ms to 2048 ms, while in the 32-cps-bandwidth the change is a factor of 4.0. On the other hand, the 0.5-cps-bandwidth appears to exhibit a minimum at pulse lengths in the region between 128 and 512 ms.

In order to decide whether the minimum in the 0.5-cps bandwidth truly existed, a rank test (7) was used. The data were pooled for the two intermediate pulse lengths and for the longest and shortest pulse lengths and

Table 1

Average Intensity DL (db) for each Subject for All Stimulus Conditions Tested

Subject A

| BAND-WIDTH | 32 ms | 128 ms | 512 ms | 2048 ms |
|---|---|---|---|---|
| 0.5 cps | – | 1.85 | 1.53 | 2.17 |
| 2 | 4.00 | 2.58 | 2.88 | 1.60 |
| 8 | 4.30 | 1.53 | 1.40 | 1.34 |
| 32 | 2.14 | 2.47 | 1.28 | 0.58 |
| sine | – | 3.13 | 1.29 | 1.19 |

Subject B

| BAND-WIDTH | 32 ms | 128 ms | 512 ms | 2048 ms |
|---|---|---|---|---|
| 0.5 cps | 2.36 | 2.03 | 1.20 | 1.94 |
| 2 | 1.58 | 2.00 | 2.23 | 1.46 |
| 8 | 2.55 | 2.15 | 2.41 | 1.21 |
| 32 | 2.76 | 1.78 | 1.10 | 0.90 |
| sine | 3.35 | 1.28 | 0.83 | 0.83 |

Subject C

| BAND-WIDTH | 32 ms | 128 ms | 512 ms | 2048 ms |
|---|---|---|---|---|
| 0.5 cps | 3.85 | 2.94 | 3.24 | 4.40 |
| 2 | 2.10 | 2.78 | 2.59 | 2.24 |
| 8 | 4.50 | 3.23 | 2.28 | 1.56 |
| 32 | – | 2.79 | 1.41 | 1.66 |
| sine | – | – | 1.61 | 1.05 |

Subject D

| BAND-WIDTH | 32 ms | 128 ms | 512 ms | 2048 ms |
|---|---|---|---|---|
| 0.5 cps | 3.85 | 2.93 | 3.62 | 2.50 |
| 2 | 2.98 | – | 3.23 | 2.62 |
| 8 | – | 2.66 | 2.28 | 2.37 |
| 32 | 3.85 | 2.27 | 1.45 | 1.47 |
| sine | – | – | 1.49 | 1.27 |

Subject E

| BAND-WIDTH | 32 ms | 128 ms | 512 ms | 2048 ms |
|---|---|---|---|---|
| 0.5 cps | 4.02 | 1.32 | 2.43 | 2.08 |
| 2 | 2.57 | 2.95 | 2.23 | 1.35 |
| 8 | 4.05 | 2.52 | 1.56 | 0.82 |
| 32 | 4.90 | 2.15 | 0.84 | 0.63 |
| sine | – | 1.82 | 0.95 | 0.75 |

Subject F

| BAND-WIDTH | 32 ms | 128 ms | 512 ms | 2048 ms |
|---|---|---|---|---|
| 0.5 cps | 1.70 | 1.70 | 1.80 | 1.88 |
| 2 | 1.48 | 1.92 | 1.17 | 0.99 |
| 8 | 1.55 | 1.61 | 1.05 | 0.63 |
| 32 | 1.42 | 0.85 | 0.70 | 0.69 |
| sine | 1.24 | 0.78 | 0.58 | 0.50 |

Subject G

| BAND-WIDTH | 32 ms | 128 ms | 512 ms | 2048 ms |
|---|---|---|---|---|
| 0.5 cps | 4.50 | 3.72 | 3.03 | 2.19 |
| 2 | 3.35 | 3.14 | 2.33 | 2.45 |
| 8 | 5.55 | 3.33 | 2.16 | 0.92 |
| 32 | 4.10 | 3.07 | 1.28 | 0.88 |
| sine | 2.92 | 3.14 | 2.26 | 1.26 |

analyzed. It was found that the DLs for the medium pulse lengths were lower than the other two at the .06 probability level. However, this significant difference may have been due mostly to the high thresholds obtained at the 32-ms pulse length. Therefore, an additional analysis was made on the thresholds obtained at the 128-ms, the 512-ms, and the 2048-ms pulse lengths. It was found that in 5 out of the 7 Ss, thresholds obtained at either or both of the intermediate pulse lengths were lower than thresholds obtained at the 2048-ms pulse length. Again using a rank test, it was found that a lower threshold in 5 out of 7 cases was significant at the .05 level.

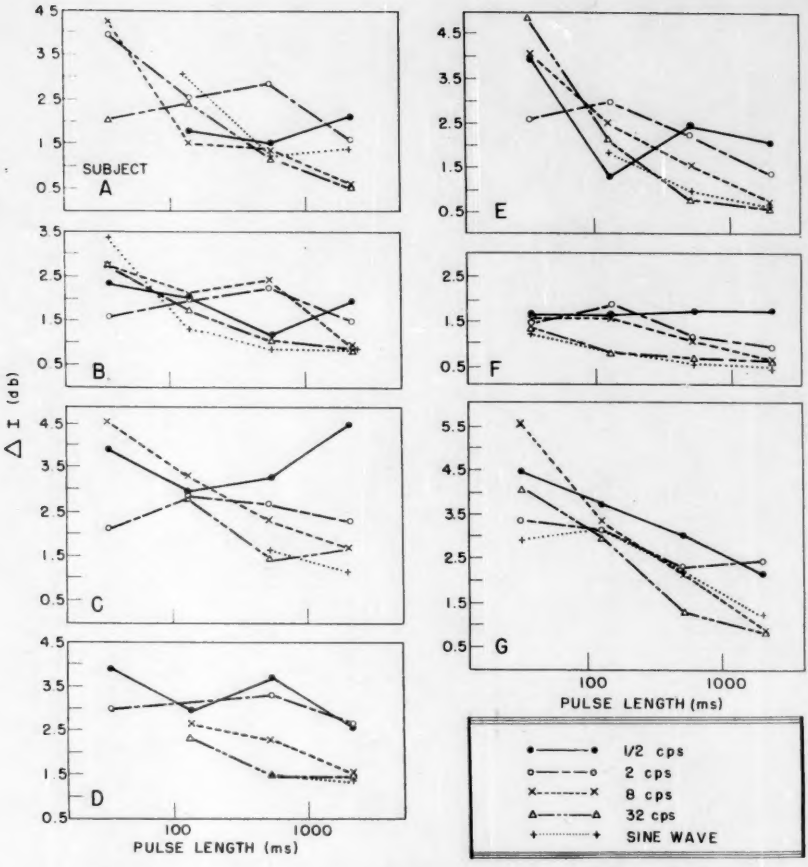


Fig. 3 Intensity difference thresholds for four bandwidths as a function of pulse length and subject

The low slope of the 2-cps bandwidth function appears to indicate a threshold that is independent of pulse length. The threshold obtained for the four pulse lengths were analyzed by the same rank test. It was found that the differences among the pulse lengths were significant at the .05 level. It seems reasonable to conclude only that there is a change in threshold with pulse length for the 2-cps bandwidth. However, it is not as great as for the wider bandwidths.

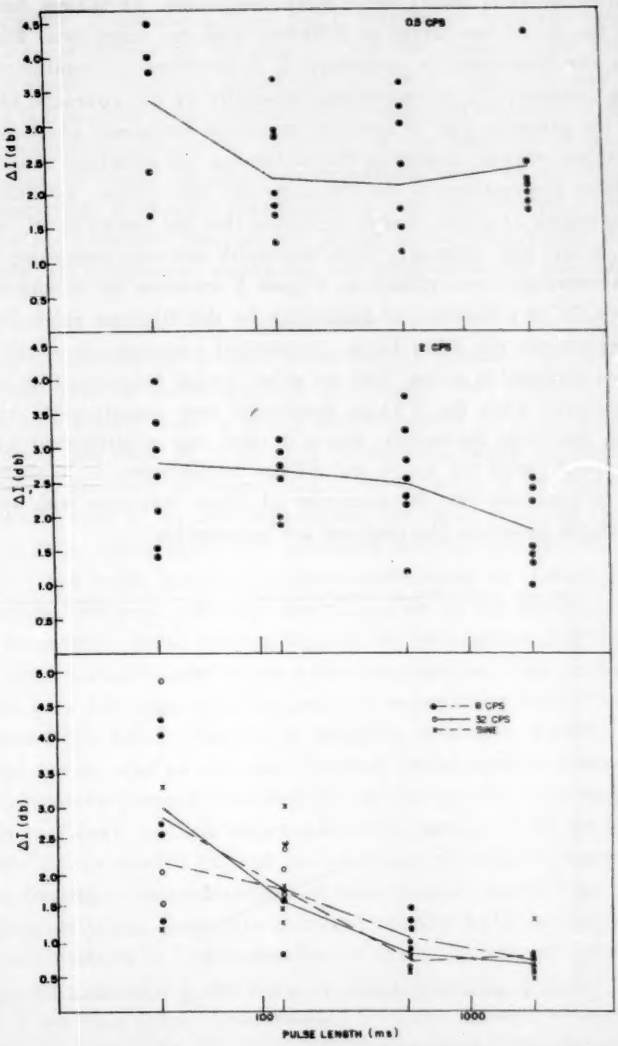


Fig. 4 Composite curves of intensity discrimination as a function of pulse length for the different stimuli

It was origionally hypothesized that signals with perceptually identical envelope characteristics would yield identical intensity DLs. Comparisons among DLs for 8-cps and 32-cps bandwidths of noise and a pure tone indicate that for durations of 32, 128, and 2048 ms there were no significant differences among these three conditions. At 512 ms, however, the DL for the 8-cps bandwidth is different from the other two. With this exception, the hypothesis is confirmed. It is therefore reasonable to conclude that the intensity DL is determined primarily by the envelope characteristics of the stimulus and is independent of the frequency characteristics of the stimulus, except insofar as they determine the envelope characteristics.

When fluctuations in the envelope are perceptible, as with very narrow bandwidths of noise, it was predicted that the intensity DL would rise. The DL would rise inversely with bandwidth because smoothing would become increasingly less effective. Figure 5 presents the intensity DLs for the seven Ss as a function of bandwidth for the 2048-ms pulse length. The curve represents the mean limen. Statistical examination of the intensity difference thresholds at the 2048-ms pulse length indicated that the threshold associated with the 0.5-cps bandwidth was significantly higher than that with the 2-cps bandwidth, which in turn, was significantly higher than the thresholds with the 8-cps and 32-cps bandwidths. It is therefore reasonable to conclude that the intensity DL rises inversely with noise bandwidths whose envelope fluctuations are perceptible.

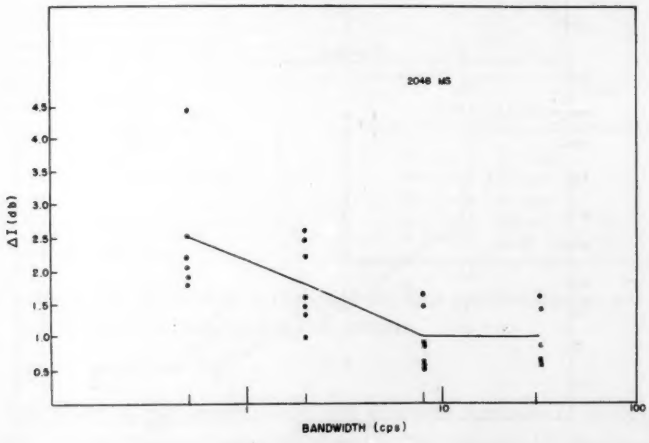


Fig. 5 Threshold as a function of bandwidth for 2048-ms pulse lengths

It was also hypothesized that when the pulse length of the narrow-bandwidth noise stimuli were reduced to the point where the envelope did not vary over pulse length, there should be no differences between narrow and wide bandwidths of noise. An analysis of variance was performed on the data for the 32-ms and 128-ms pulse lengths. A separate analysis of variance was performed on the data for the two longer pulse lengths. A summary of these analyses is presented in Tables 2 and 3. It may be seen in Table 2 that significant differences were observed between all the major variables including bandwidths. However, in the analysis of the shorter pulse lengths, all major variables are significant with the singular exception of bandwidth. It appears reasonable to conclude that as pulse length is reduced and envelope fluctuations in the narrow bandwidths are eliminated, threshold differences among the four bandwidths are also eliminated.

## DISCUSSION

The purpose of the present study was to examine the way in which an envelope detector model applied to intensity discrimination. Four hypotheses were stated, each of which involved some envelope property. Results showed that three of these were directly validated: (a) intensity discrimination is the same for those stimuli whose rates of fluctuation exceed the smoothing time of the auditory system; (b) where envelope fluctuations are perceptible, the intensity DL increases directly with decreasing bandwidth; (c) when pulse length is reduced sufficiently to eliminate perceptible envelope changes, intensity discrimination is the same for all bandwidths. In general, these results support the assumption that the auditory system acts fundamentally as an envelope detector. The analog may be described as a bandpass filter followed by a nonlinear device followed by a low-pass filter which operates an intensity sensitive device.

One reason why an envelope detector model appears reasonable lies in the differences obtained between the narrow and the wide bandwidths of noise. In the latter, no differences in threshold occurred for the 8-cps bandwidth, the 32-cps bandwidth, and the pure tone. In spite of the wide differences in frequency characteristics of these stimuli, as well as their envelope characteristics, they were detected equally well. Intensity discrimination thus appears to be independent of the stimulus frequency as such. However, the similarity in threshold is very reasonable in terms of the model. With a low-pass filter of the order of 6-10 cps, signals whose envelopes fluctuate at a rate faster than this will be smoothed. This feature suggests a direct and probably peripheral neural integrating process.

For the narrow noise bandwidths, narrower than 8 cps, smoothing be-

comes increasingly ineffective. Fluctuations in intensity over the pulse duration become perceptible, and estimation of the intensity of the stimulus becomes more difficult. Detection of differences between two such stimuli is therefore poorer, as the results indicate. Again, the ordering of the thresholds for the 2048-ms pulse length is what the model predicts.

Table 2

Summary of the Analysis of Variance Between 32-ms and 128-ms Pulse Lengths for the 4 Bandwidths and 7 Subjects

| Source | df | Mean Square | F |
|---|---|---|---|
| Pulse Length | 1 | 7.24 | 17.66[1] |
| Bandwidth | 3 | 0.66 | 1.61 |
| Subjects | 6 | 6.49 | 15.83[1] |
| PL x BW | 3 | 1.49 | 3.63[2] |
| PL x Ss | 6 | 1.59 | 3.88[1] |
| BW x Ss | 18 | 0.64 | 1.56 |
| PL x BW x Ss | 18 | 0.49 | 1.20 |
| Within | 45 | 0.41 | error |
| Total | 100 | | |

[1] $p < .01$
[2] $p < .05$

Table 3

Summary of the Analysis of Variance Between 512-ms and 2048-ms Pulse Lengths for the 4 Bandwidths and 7 Subjects

| Source | df | Mean Square | F |
|---|---|---|---|
| Pulse Length | 1 | 6.40 | 13.62[1] |
| Bandwidth | 3 | 13.40 | 28.51[1] |
| Subjects | 6 | 5.14 | 10.94[1] |
| PL x BW | 3 | 0.63 | 1.34 |
| PL x Ss | 6 | 0.01 | – |
| BW x Ss | 18 | 0.31 | – |
| PL x BW x Ss | 18 | 0.91 | 1.94[2] |
| Within | 100 | 0.47 | – |
| Total | 155 | | |

[1] $p < .01$
[2] $p < .05$

Conversely, when the pulse length for the narrowest bandwidths is reduced, there may be insufficient time for fluctuations to occur. From the model, it is predictable that elimination of fluctuations by pulse length reduction should also eliminate differences in threshold among the four bandwidths. This is also what the results indicate.

However, while reduction of pulse length reduces the number of fluctuations in noise, two other events occur at the same time. First, the spectrum characteristics of the narrow bandwidths of noise are different for short pulses than for long. Although it is true that there are no fluctuations in the envelope for short pulses, short samples of noise may have characteristics bearing little resemblance to longer samples of narrow bandwidths of noise. The spectrum of a 32-ms pulse is of the order of 32 cps, at least for the pure tone. Thus, a 0.5-cps bandwidth at the output of the filter is considerably wider on pulsing.

Second, the statistical characteristics of a short sample of noise may not be of the form determined by the filter. The filter is a weighting function which determines the mean value of the amplitude of each frequency component of the noise. The reliability of the mean is dependent upon the sample size, or in this case, the pulse duration. For short pulses, the spectrum of the noise may differ extensively from that expected on the basis of the filter characteristic. This was quite noticeable to the subjects for the 0.5-cps bandwidth of noise. One pulse would often bear little resemblance to another in its spectral characteristics. One pulse might have a definite pitch quality while another might sound broadband.

Interpretation of the results on the effect of shortening the pulse length must be tempered by these two conclusions. Reduction of pulse not only eliminates envelope fluctuations, it also is associated with smearing the distinctions between narrow and wide bands of noise; and short samples of narrow bandwidth noise may bear little resemblance to longer samples.

One thing of significance is that discrimination is possible even when the stimulus is perceptibly varying. From Fig. 4 it may be seen that the intensity DL appears to decrease for the 2-cps bandwidth as the maximum number of expected fluctuations in the envelope increases from 1 to 4. This suggests that the decision making process involves a further statistical operation. Indeed, discrimination, in the last analysis, appears to depend upon a detection of differences between the statistical parameters derived from the stimuli.

Up to this point, the discussion has been concerned mainly with the two factors of pulse length and fluctuations in the stimulus envelope. From the model and the statistical nature of decision, any perceptible variations in the stimulus envelope might be expected to degrade the threshold. In the two narrow bandwidths, perceptible but monotonic variations may be expected for pulse lengths between 128 and 512 ms. The statistics of these changes are complex, but certain general statements may be made. The distribution of envelope slopes is a random variable for independent samples. The distribution appears to be symmetrical with a mean slope of zero. The variance of the distribution appears to be determined primarily by bandwidth, varying directly with it.

As was mentioned, the prediction of the model is that any variations in the envelope characteristics of the stimulus should degrade the threshold. With this, and the statistics of the distribution of envelope slope, the threshold curves for the 0.5-cps and 2-cps bandwidths may be clarified. For a noise of 0.5-cps bandwidth, from pulse to pulse, the variance of the slopes should be small, especially relative to the 2-cps bandwidth. In this case, the uncertainty in estimating the pulse loudness and, thus, the differences between pulses should be less also. For the 0.5-cps bandwidth at 512 ms, threshold degradation due to pulse length alone is small; fluctuations do not exist, and variations of intensity over pulse length is small. All these factors optimize conditions for detecting differences in intensity, and the DL is a minimum at around 500 ms for the 0.5-cps bandwidth, as the trend in the data indicates.

Examination of the pulse length function for the 2-cps bandwidth shows a lower slope than for the wider bandwidths. Actually the differences among the four pulse lengths only reaches the .05 level of significance. The improvement in threshold due to increasing pulse length seems to be reduced, especially in the region of 32 to 512 ms. In this region, the amplitude of the envelope may change only monotonically. The slope of the envelope function may be considerably greater in the 2-cps bandwidth than that expected for the 0.5-cps bandwidth. If a perceptible change in envelope amplitude degrades the limen, then the DL for the 2-cps bandwidth should be more degraded than the DL for the 0.5-cps bandwidth. At the same time, however, there is an improvement in threshold due to increasing pulse length in the pulse length range of 32 to 512 ms. Thus, two opposing effects are operating: one to improve, the other to degrade discrimination. If the two effects are about equal, the net result should be that the threshold will change very little over this range of pulse lengths. This

is a reasonable conclusion to be drawn from the data, where there is very little change with pulse length for the 2-cps bandwidth.

More generally, where conditions of pulse length and envelope variation may be optimized, threshold for the narrow-bandwidth stimuli will exhibit a minimum. For the 2-cps bandwidth no optimum region exists, and the two factors of pulse length and slope magnitude interact to maintain a high threshold. An optimization did occur for the 0.5-cps bandwidth at or around a pulse length of 0.5 seconds. However, even at its minimum, the DL for a 0.5-cps bandwidth was generally higher than for the pure tone. This indicates that variations are small but still perceptible. A reasonable prediction is that further reduction of bandwidth would place the minimum at a longer pulse duration and the value of the threshold at the minimum should approach that of the pure tone. The essential point of this discussion is that any perceptible variations in the stimulus envelope do, in fact, degrade discrimination. The perceptual problem before the listener is very little different for the case of fluctuation and monotonic change. The same decision process probably applies equally in both cases.

The data obtained in this study are consistent with an envelope detector or critical band model. Three processes appear to be involved in making intensity discriminations. One seems to be directly related to pulse duration. Considering the nature of the statistical operations suggested, it is tempting to speculate that pulse duration is analogous to sample size. Thus increasing pulse length, like increasing sample size, increases the reliability of the differences between stimuli. A second process seems to be a direct smoothing implicit in the model. Third, there appears to be a more complex averaging over the variations in the noise when those variations are perceptible. All three of these processes describe a complex, time-dependent system operating in the intensity domain. One part involves a peripheral or integrating mechanism and the other involves a central or integrative process.

The problem which initiated the present investigation was the relation between intensity and frequency discrimination. In the previous research (1) it was found that a simple linear equation predicted the frequency DL for noise bandwidths greater than 8 cps. The two determining quantities in this equation were the critical bandwidth and the intensity DL, both of which were assumed to be constant over the range of conditions tested. For narrower bandwidths, the simple relation broke down. The critical bandwidth was invariant; hence if the equation were correct, the frequency DL increased due to corresponding increases in the intensity DL with narrow bandwidths of noise. Qualitatively, the results of the present

experiments furnish strong confirmation of this prediction. For long pulse durations, which were employed in the previous frequency discrimination study, the intensity DL of the present study is constant for bandwidths of 8 cps and above, and increases inversely with bandwidth below this.

It was further suggested that in this narrow-bandwidth region, for a fixed pulse length, the intensity DL should reach a maximum for that bandwidth in which fluctuation could still occur. Beyond that, the intensity DL should rapidly decrease for narrower bandwidths, because the pulse length was too short for fluctuations to occur. In light of the fact that monotonic variations in the envelope affect intensity discrimination, in addition to envelope fluctuations, it now seems reasonable to extend the earlier prediction to include monotonic changes in the envelope as well as fluctuations. Thus, for pulse lengths and bandwidths in which only monotonic and perceptible changes in envelope may occur, the intensity DL will vary directly with the magnitude of that change. So also should the frequency DL. This should generally occur for the wider of these bandwidths. In any event, whenever there is a perceptible variation in the stimulus envelope, the frequency DL will be higher than it would be if the slope of the envelope were zero as with a pure tone.

Quantitatively, however, it should be pointed out that the intensity DLs of the present study do not lead to an exact prediction of the frequency DLs of the previous study. It appears that the fluctuations associated with the narrow bandwidths of noise produce intensity DLs even higher than that required for prediction of the frequency DLs. As pointed out in the previous discussion, the total energy over the long time interval for the narrow noise bandwidths is not perfectly correlated with the perception of intensity. Thus, the observed intensity DLs based upon total energy might be expected to be somewhat higher than the intensity DLs required for prediction of the frequency DLs.

In substance, the present experiment and its predecessor have sampled the domain of narrow-bandwidth auditory signals as they apply to frequency and intensity discrimination. A consistent picture emerges. Frequency and intensity discrimination are directly related. When the fluctuations in the noise envelope exceed the smoothing time of the auditory system, the intensity DL is constant and the frequency DL varies linearly with bandwidth. For narrow bandwidths, where the rate of fluctuation is less than the smoothing time of the system, both frequency and intensity discrimination deteriorate. This deterioration is not confined to fluctuations in the slope of the envelope, for it may be observed with monotonic variations in the envelope.

Both of these studies suggest an analog for the description of frequency discrimination. This is that the auditory system acts as if it were a single-tuned circuit, i.e., a filter whose response characteristic approximates a normal curve. This filter then is followed by an envelope detector. However, to obtain optimum discrimination, this model requires that discrimination be made through the detection of changes in intensity on that portion of the input filter characteristic having the maximum slope. That is, along the steepest portion of the filter curve there is a maximum change in intensity for the smallest shift in frequency. Thus, utilization of the gradient rather than the peak of the filter optimizes discrimination. More generally, the analog representation of the discriminator is a normal resonant filter with a bandwidth of approximately 50-100 cps (2) followed by an envelope detector containing a low-pass filter of approximately 8 cps. The output of the envelope detector feeds an intensity discriminator operating on the skirts of the input filter.

*Implications for a Theory of Discrimination*

The above discussion defines an analogy to the way in which the auditory system operates. It is by no means an explanation of the neurological system. What it does demonstrate is that frequency and intensity are interdependent in the auditory system. The question is: by what set of transformations does frequency discrimination become dependent upon intensity discrimination?

One way to approach the question is to examine the neural representation of intensity. The fundamental means by which stimulus amplitude is coded in the nervous system is by the rate of neural activity – a time operation. In the auditory system, this neural output occurs on only a portion of the stimulus cycle. This leads to bursts of activity associated with the stimulus frequency. This synchronous discharge thus represents an interaction between intensity and deformation of the basilar membrane. However, synchrony is a very common phenomenon in neural systems, and serves at least one very useful function. Synchronous discharge tends to insure the arrival of a sufficient number of impulses at a synapse so that summation may occur, and so aid in the transmission of the fundamental intensity information.

Beyond the first synapse, firing should become decreasingly correlated with stimulus periodicity. Synapses, in one sense, act as integrators which fire only if the incident impulses are sufficient to achieve summation. The output of spikes of the synapse may have a periodicity, but it should not be directly related to the stimulus frequency. Nevertheless, this property of periodic firing will still exist in postsynaptic neurons. Such

time coherence is a requisite for summation at later synapses. Thus, in neural transmission, the frequency of firing is consistently related to stimulus intensity but need not be so related to stimulus frequency.

Synchrony may do more than merely preserve intensity information. It may also serve as a spatial sharpening mechanism. If there is any extensive overlapping of collateral fibers, summation at the overlapped synapses will depend upon the impulses arriving in time coincidence. If the stimulus generates a deformation pattern, rate of firing of neurons along the slopes of this deformation pattern will differ from those at the peaks. This will lead to a decrease in time coherence among the impulses arriving at the overlapped synapse. Since the period of latent addition is so brief, it is not unreasonable that summation will be less likely at these synapses displaced from the peak of activity. Not only will the probability of summation be reduced, but also suppression may occur. Impulses arriving aperiodically at a synapse can cause a rise in the threshold of the synapse or suppression of the presynaptic fibers. It seems reasonable that such a process may act to sharpen the gradient of the deformation pattern, and the sharpening may be further improved by repetition of the process at higher order synapses.

The neurological mechanisms described are essentially those of reciprocal overlap and multiplication of pathways. They have been utilized by Marshall and Talbot (8) in a theory of visual acuity and by Ruch (9) as an explanation of the two-point tactile limen. There is substantial evidence that both processes exist in the auditory system (10). The fundamental point, however, is that the auditory system may utilize as a cue to localization the gradient of activity generated by the stimulus rather than the peaks. In the manner outlined, the gradient sharpening would yield a discontinuity in neural activity leading to sharp localization.

Viewing the auditory cortex, this feature becomes even more reasonable. The work of Tunturi (11) indicates that for a pure tone input a restricted band of activity occurs. This band is relatively narrow and has fairly sharp limits (12). That is, the demarcation of the band is fairly precise. As a matter of fact, the sharpness of this demarcation need have a slope only 6 to 10 times greater than that of the origional deformation pattern on the basilar membrane in order to account for most of the data on frequency discrimination.

Within this framework it is possible to describe a way in which frequency discrimination may be made. Assume 2 stimuli are presented successively. Through the process described, a band of activity with a sharp gradient is projected on the cortex and stored. With the second stimulus,

the cortical band is shifted slightly. If the change in rate of activity along the cortical gradient of the first band due to the presence of the second stimulus is detectable, then a shift in location, or frequency is perceived. Thus, it is the change in activity or intensity along the gradient that determines the detection of differences in frequency.

The theory outlined is primarily a place theory, but it is one in which the gradient of activity is sharpened rather than the peaks. However, this theory also requires time coherence, for by this means is obtained the synchrony required for the proper development of the inhibitory processes needed for sharpening. In this sense, the theory proposed is duplex, except that the periodicity of the stimulus contains no information – it is only a means for guarantying synchrony in neural response.

This discussion has oversimplified the transformation done by the auditory system and it certainly is incomplete. There are several more indirect inhibitory mechanisms that can operate to sharpen the gradient of activity. There are 2 conclusions, however, that derive from this discussion. First, analysis in the auditory system is not performed at some particular level. Rather, transmission, transformation, and analysis occur simultaneously and continuously in the auditory system. Second, auditory theory has generally sought some direct correspondence between the properties of the stimulus and the neural transformation. This need not be true, and indeed it appears that the relation between stimulus and neural response may be quite indirect.

## SUMMARY

Upon the assumption that the auditory system operates in a manner analogous to an envelope detector, a series of hypotheses were stated predicting how intensity discrimination would be influenced by the variations in the stimulus envelope. Filtered random noise of four different bandwidths and four pulse durations was used to vary rate and number of envelope fluctuations. Seven listeners were used and they heard two pulses of noise in succession, judging the intensity of the second relative to the first. The physical differences between the stimuli were determined by taking the ratio of the total energy contained in each pulse. A transition curve for the responses to the various stimulus differences was plotted and the difference limen taken as the probable error of the fitted curve. The results indicated that discrimination was the same for stimuli whose envelopes were smoothed by the auditory system despite differences in frequency spectrum. For stimuli whose envelope fluctuations occurred at a rate less than the integrating time of the auditory system, discrimination was degraded, in-

creasingly so as bandwidth was reduced. However, the differences among bandwidths were eliminated when pulse duration was reduced sufficiently to preclude envelope variations.

This research generally validates the use of an envelope detector model. The auditory system does appear to operate in a manner consistent with such a model. The results suggest that the auditory system operates as if it were a circuit containing a normal resonant filter having a bandwidth of 50-100 cps. This is followed by a nonlinear element and in turn by a low-pass filter of 6-10 cps bandwidths. The output of the low-pass filter operates a statistical decision process. This detects differences between the characteristics of the distributions generated by the stimulus acting within the auditory system.

Applying the results of this research to the data on frequency discrimination does, indeed, lead to the conclusion that frequency discrimination is dependent upon intensity discrimination. From the envelope detector model a linear equation derives in which the frequency DL depends upon 2 variables: the bandwidth of the input filter and the intensity DL. Where the intensity DL is constant, as in wide-band noise, the frequency DL rises directly with noise bandwidth. For noise stimuli whose bandwidths are less than 8 cps in which the intensity DL rises, so does the frequency DL, even though frequency localization is improved by the bandwidth reduction. The only additional requirement for the prediction of frequency discrimination is that detection of differences takes place on that portion of the input filter characteristics having maximum slope.

The results suggest certain neurological correlates for discrimination. By means of the mechanism of reciprocal overlap, the deformation pattern on the basilar membrane may be sharpened. What is especially important is that the gradient of that activity pattern be sharpened in order to obtain a near-discontinuity between active and inactive regions in the central nervous system. For only by detecting changes in rate of neural activity that occur along such a border can precise discrimination occur. The detection of changes in rate of neural activity is, in essence, the detection of changes in intensity. However, in order to obtain a sharp border a synchrony in neural firing is required, for only through periodic discharge can there be established the inhibition and facilitation required for sharpening. Whenever pulse length is too short or stimulus intensity varies slowly enough, there is an insufficient amount and rate of activity to bring these sharpening mechanisms into play, and thus discrimination is degraded. The neurological processes suggested generally lead to the same conclusion as the analog. However, the input filter extant in the electrical model appears in the nervous system to be an end product of the neural operation.

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# COMPARISON OF THE ATTENUATION CHARACTERISTICS OF THE ACOUSTIC REFLEX AND THE V51–R EARPLUG

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## ABSTRACT

Previous research has shown that temporary threshold shifts of individuals exposed to impulse noise were significantly smaller when they were presumably protected by having the acoustic reflex activated prior to exposure as compared to exposure without such activation. However, no inference could be drawn from those data concerning the actual attenuation value of the reflex action. In order to investigate the attenuation of the acoustic reflex, pre-and post-exposure thresholds were obtained for 13 subjects exposed under two conditions to 100 rounds of machine-gun fire (fired singly). In condition I the acoustic reflex was activated to protect the listener; in condition II protection was afforded by V51–R earplugs. Results show that protection by the acoustic reflex is superior to that of V51–R plugs up to 1000 cps, while the plugs provide more protection at and above 2000 cps.

## INTRODUCTION

Previous research (1) demonstrated that a sufficiently loud alerting signal presented just prior to each exposure to repeated impulse noise resulted in significantly smaller temporary threshold shifts than when exposure was not preceded by an alerting signal. The alerting signal used was of a frequency and intensity calculated to activate the intra-aural muscles. These muscles, when contracted as a result of acoustical, electrical or mechanical stimulation constitute the acoustic reflex or AR, and have been shown to damp high level sound transmission through the middle ear (2, 3, 4).

Results of previous studies were not in a form to permit comparison of the protective characteristics of the AR with those of other commonly used protective devices. The lack of data regarding the relative amounts of protection afforded man by AR action suggests that it would be worthwhile to determine, under identical conditions, TTS of subjects exposed to impulse noise while protected by reflex action compared with TTS when protected by a good commercially available protector (in this case the V51 –R earplug).

The term protection is used in this study rather than attenuation because TTS in db following exposure to noise is the criterion and this measure is not felt to be similar to the free field threshold shift method used in obtaining attenuation data on conventional ear protective devices. This

method, needless to say, is hardly appropriate for measuring the attenuation of the reflex.

There are conflicting results in the literature regarding the frequency attenuation characteristics of AR action. Wiggers (3, 4) in an electrophysiological study on animals reports about 45 db attenuation at 100 cps and says that "during contractions of the tensor tympani and the stapedius transmission loss increases linearly with a decrease in frequency." In another investigation, Wiggers found that most of the attenuation effect is on tones of 1000 cps or less.

Galambos and Rupert (2), on the other hand, found that the reflex attenuates transmission of tones about 20–22 db between at least 500 and 3000 cps and significantly protects the ear against damage from intense sounds. These results are more in line with the study of Fletcher and Riopelle (1) which indicated that good protection (in db TTS) was provided for frequencies up to 1000 cps and considerable protection for frequencies above 1000 cps. Simmons (5) reports attenuation greater for 2000 cps and below with middle ear muscle decreasing above that frequency until at 7000 cps little or no identifiable protective activity remained.

If the acoustic reflex is indeed more efficient or at least as efficient in attenuating low frequencies as high frequencies, it might possibly be a solution to providing adequate protection against sounds with high energy levels in the low frequencies. Many problems, including those of fit, seal, and piston action of the device, prevent existing devices from approximating the bone conduction limits of attenuation at low frequencies. The 45 db at 100 cps found by Wiggers, for example, is almost twice the attenuation provided by the best available commercial protector.

The V51–R earplug was selected as the protector for comparison with the AR because of its wide use and the considerable body of literature available regarding its attenuation characteristics.

Attenuation characteristics for the V51–R, as reported in the Benox report (6), show attenuation of 28 db at 100 cps, 30 db at 500 and 1000 cps, 42 db at 2000 cps, 38 db at 3000 cps, 33 db at 4000 cps, 40 db at 6000 cps and 42 db at 8000 cps.

## METHOD

Prior to data collection complete otological examinations were made of all S's used in this experiment. Wax was removed where indicated and all persons with fluid in their ears were disqualified from participation. All S's participating had negative ENT findings. Thirteen S's, trained in using the Bekesy audiometer to determine their thresholds, were brought in singly and their threshold obtained immediately before firing. Then 100 rounds of

ammunition were fired, one round at a time, from a 30 cal. machine gun. As soon as firing ceased their threshold was again determined.

Threshold tracings were begun within 8–30 sec. after the last round was fired. The thresholds were for sweep frequencies from 250–8000 cps. Each S was exposed to one course of firing with no protection, one with the AR activated, and one with V51–R earplugs. Pre- and post-exposure audiograms for each condition were examined to establish post-exposure TTS. The TTS's from the two experimental conditions were then subjected to analysis of variance to determine the significance of the differences obtained.

## RESULTS

Results show that there was a significant difference (1% level of confidence) in the attenuation provided by the reflex and the plug. Figure 1 plots the TTS's resulting from exposure to the firing noise for all three conditions. Overall mean TTS was 19.23 db with no protection, 6.27 db with the acoustic reflex, and 2.51 db when protected by the V51–R. Subjects in this experiment differed significantly among themselves with regard to TTS. The raw data showed that 5 of the 13 S's had little or no TTS after unprotected exposure to the firing noise. Of those with post exposure threshold shifts, some appeared almost completely protected by both the

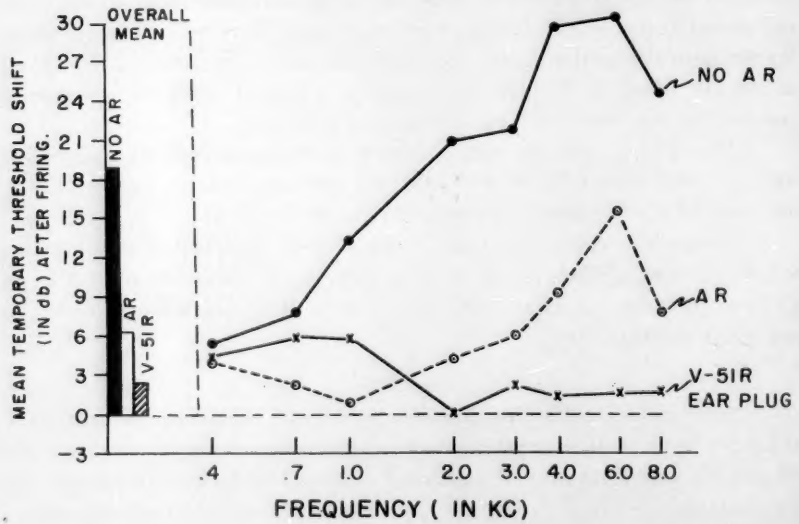


Fig. 1. Mean temporary threshold shift induced by three experimental conditions.

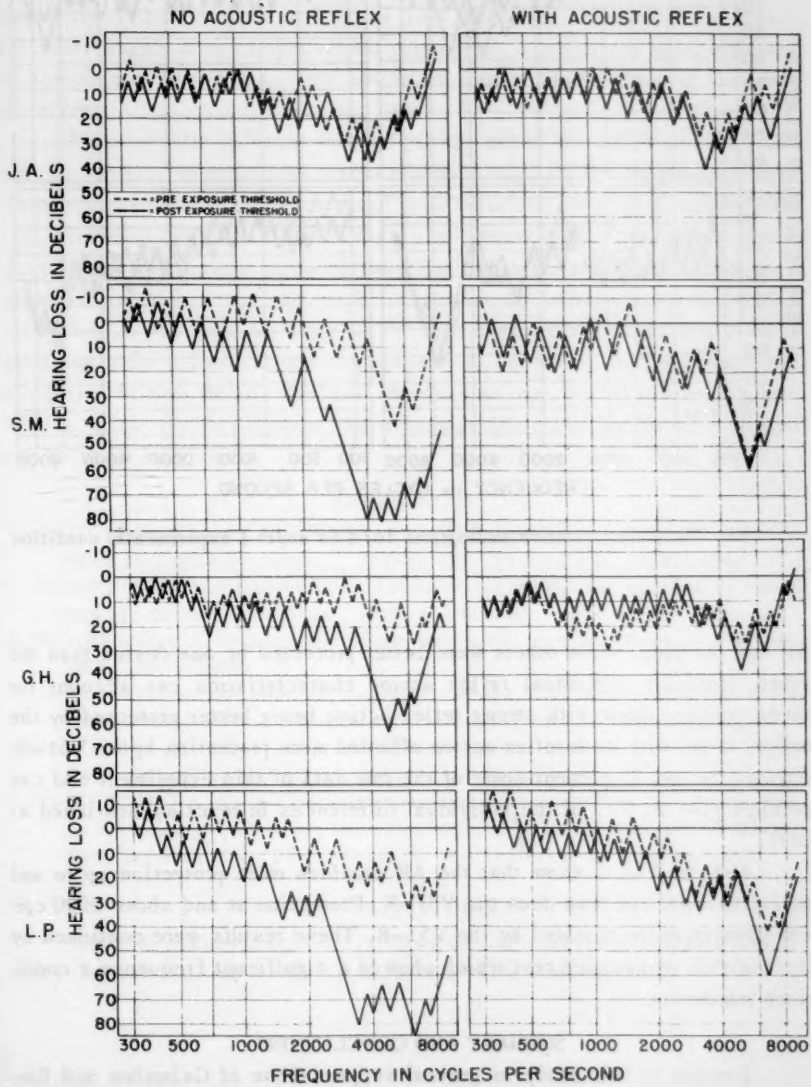


Fig. 2a. Representative audiograms for 4 Ss under 2 experimental conditions

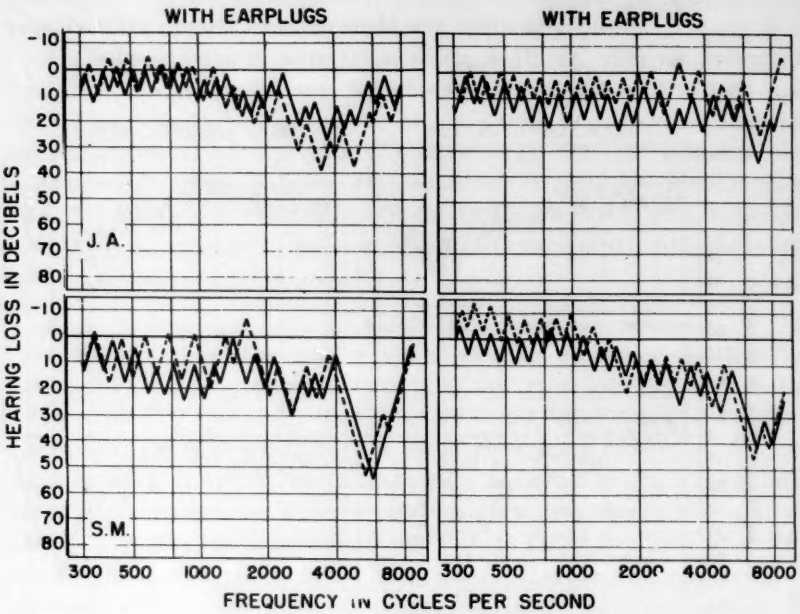


Fig. 2b. Representative audiograms for 4 Ss under 1 experimental condition

AR and the plug, while others were better protected by one device than the other. Possibly individual reflex action characteristics can account for these results, those with strong reflex action being better protected by the reflex, those with weak reflex action afforded more protection by the V51–R. Figures 2a and 2b present some of the raw data of this experiment and can perhaps give an idea of the individual differences in reaction mentioned above.

Data in Fig. 1 show that the AR provides more protection up to and including 1000 cps than does the V51–R. Protection at and above 2000 cps was greater while shielded by the V51–R. These results were confirmed by the analysis of variance test which showed a significant frequency x conditions interaction.

## SUMMARY AND CONCLUSIONS

Results of this study in general support those of Galambos and Rupert (2) in that protection was found for frequencies as high as 8000 cps, while, in line with Simmons (5) findings we found relatively better protec-

tion at and below 2000 cps. Some support is made of Wiggers (3, 4) in that good protection (compared to that of the V51–R) was provided for frequencies up to 1000 cps.

Consideration of the attenuation characteristics and the TTS protection of the V51–R earplug, and of the TTS protection afforded by the acoustic reflex suggests to us that reflex attenuation is relatively more efficient at low than at high frequencies but by no means non-existant at high frequencies.

These results indicate that protection use of the reflex should probably be confined to situations where energy is high for low frequency sound. Certainly the V51–R is cheaper and more efficient for sounds above 2000 cps, providing the situation demanding ear protection is one where insert devices are appropriate. An additional limitation on use of the reflex as a protector is that it must be used for impulse or intermittent sound. This limitation is imposed by virtue of the fact that the reflex adapts or fatigues out after a time. Another advantage of the reflex over conventional protection is that fit and seal are not critical with regard to ensuing protection. Also, piston action of the ossicular chain can hardly be expected even at high intensities.

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## ACKNOWLEDGEMENTS

Grateful acknowledgement is made to Capt. David A. Hilding and E. Allen Schmidt and Ira Rubin for their help with this research.

# NEGLIGIBLE EFFECTS OF X-RADIATION OF THE HEAD UPON HEARING IN THE RAT

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## INTRODUCTION

Traditionally the ear has been regarded as a rather stable system, essentially mechanical in its transmission of vibrations from the air to the fluids of the inner ear, and essentially also mechanical in the consequent movements of the basilar membrane, and the production of electricity by the hair cells when they are deformed by shearing stresses. As a mechano-electric system, only the gross details of tissue status have generally been considered; the details of oxygenation, circulation, nutrition, electrical pools, blood-endolymph barriers, etc. have not generally been studied.

In recent years, however, from laboratories too numerous to mention have come studies which have dramatically broadened our concept of the auditory mechanism. It is apparently sensitive to many variations of metabolism, enzyme activity, electrolytic balance, autonomic nervous system regulation, peripheral circulation, and general tissue status in a way not previously envisaged. Based upon such an outlook, quite a number of therapeutic practices involving drugs, diets, and hormones are now being advocated on a more rational basis.

With respect to X-radiation, the ear would at first thought be considered well protected and relatively immune to cellular or other changes. Certainly no accounts are current of unusual loss of hearing following X-radiation of the whole body or of the head, nor even following therapeutic administration of X-rays to specific intracranial locations near the labyrinth.

On the other hand, it is possible in some cases that hearing losses have actually occurred following X-radiation but that these losses were overshadowed by more crippling lesions or dysfunctions. Additional considerations are (1) that since hearing and speech both have a considerable safety factor, such that an appreciable diminution in acuity must occur before speech reception is very much deteriorated, and furthermore (2) that since a really quite large amount of frequency and intensity distortion can exist in the speech signal (and inferentially thus in the hearing mechanism) without reducing speech intelligibility very much, therefore another possibility is that in some cases hearing losses of measurable extent could have existed without disturbing the individuals overmuch.

In view of these considerations, it seemed of interest to explore the matter directly by irradiating the animal's head and searching for any changes in either the gross or some of the finer aspects of audition.

## SUBJECTS

For our purposes, it was desirable to use the most economical mammal which could be trained in fairly complicated behavior patterns upon auditory cue. The white rat seemed an obvious choice because of the existence of a dozen or more papers dating back to 1914 on auditory acuity and tonal discrimination in the rat, and because in recent years scores of papers have appeared on automated and semiautomated conditioned learning situations in that species.

Accordingly, young white rats were secured at need from the Harvard Biological Laboratories and maintained in our quarters.

## APPARATUS AND METHOD OF PRESENTING STIMULI

Equipment was assembled consisting of items with which to study the three auditory abilities outlined. Figures 1–5 show block diagrams of the several arrays.

### *(1) Audiometry by Preyer (pinna) reflex.*

See Fig. 1. A Hewlett-Packard signal generator Model 206 AR was led to a Grason-Stadler electronic switch Model 829S104, and associated timer Model 472, set for a 5-msec rise-fall characteristic and a duration of 250 msec. This voltage was led to an Altec amplifier Model 1569A, and a Stromberg-Carlson 12-inch speaker. In presenting the stimuli, the gentled animal was lightly held behind the forelegs with the ear to be tested centered on the speaker cone and 4 inches out from the plane of the cone rim. A fixed pointer guaranteed approximately the same head position for each test.

When the animal is quiescent, a single tone is sounded at a loud intensity for the experimenter. A quick and complete contraction of the pinna is usually seen. This is repeated in a leisurely sequence using tones in a decreasing series of 5-db steps. A level is soon found below which the pinna gives no response to be seen by the naked eye, but at which a slight retraction of the pinna is discernible. The massiveness of the reflex decreases *pari passu* with intensity down to this level. Two or three brief ascending and descending series suffice to establish a threshold level with at least as good repeatability as in the normal human audiogram.

The threshold sound pressure level (SPL) at the position of the pinna was measured with a calibrated condenser microphone and the Western Electro-Acoustic Laboratory's sound level meter Model 410 B.

### *(2) Audiometry by the Cochlear Microphonic (CM).*

See Fig. 2. In some rats a .007-inch hole was drilled through the promontory near the round window and an .007-inch enamelled nichrome steel wire inserted into the perilymph. Pure tones were led to the ear and

CM measured with a Hewlett-Packard Wave Analyzer Model 302 AR. CM of several fresh rats prepared in this way were averaged at a selection of frequencies to obtain a generalized curve for the normal rat relating frequency to SPL at the pinna required to yield a 1 microvolt output. This curve is usually referred to as a 1-$\mu v$ cochleogram.

A few rats yielded a 1-$\mu v$ cochleogram after X-radiation of the head as described below. This particular aspect was terminated when it became clear that the pinna reflex was furnishing the same information in a fraction of the time required.

*(3) Discrimination of Intensity Modulation.*

See Fig. 3. A General Radio signal generator Model 1303-A was led to an amplifier and speaker via an Allison rotary attenuator, with 110 db attenuation arranged linearly with rotation of the dial. The dial was arranged with a stepdown helical gear having virtually no backlash, with a 1-db change for each 15° rotation. The gear dial was attached by clamps to a General Radio oscillating gear drive Model 1750A. This drive is continuously variable both in rate and extent of rotary oscillation. When the drive controls were properly adjusted, the output of the loudspeaker was varied in a sine wave fashion through, for example, a range of 4 db, at the rate of 3 oscillations per sec. Other ranges were instantly available.

In presenting these stimuli to the small speakers (actually a group of 4 Permoflux PDR-10 phones wired in phase) placed in the animal's compartment, a tone of 4000 cps was continuously used for 5 min.

This tone in its steady state contained less than 2% harmonic distortion as measured with a Hewlett-Packard distortion analyzer Model 330 B; the tone was picked up by a Western Electro-Acoustic condenser microphone complement Model 100 E to feed into the distortion analyzer.

At random intervals and for random durations, 10 segments of this tone were given 4 db sine wave intensity modulation at 3/sec. Half of the total time was given to modulation.

*(4) Discrimination of Frequency Modulation.*

See Fig. 4. A General Radio signal generator Model 913 was fitted with an external condenser cut into the tank circuit to yield a linear change of 80 cps per 1° condenser shaft rotation. The shaft was coupled to the oscillating gear drive and controls set so that the loudspeaker frequency output varied in a sine wave fashion through, for example, a range of 4% at the rate of 3 oscillations per sec. Temporal patterns of frequency modulation vs no modulation were arranged similar to but not identical to intensity modulation as described above.

*(5) Food Reward Conditioning Apparatus.*

See Fig. 5. A restraining box of plywood 1 foot on a side with a grid

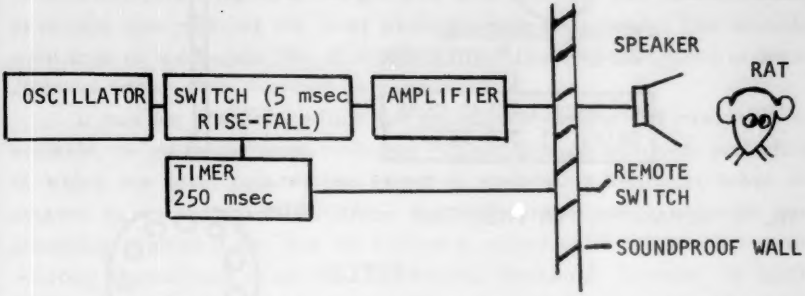


FIG. 1: APPARATUS FOR ELICITING THE PREYER (PINNA) REFLEX

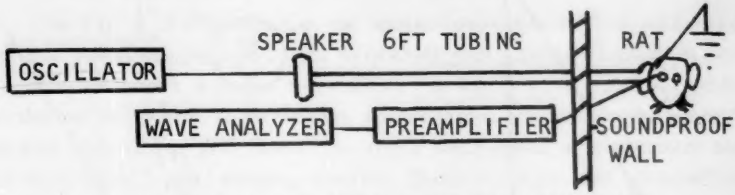


FIG. 2: APPARATUS FOR PRODUCING AND MEASURING COCHLEAR MICROPHONICS

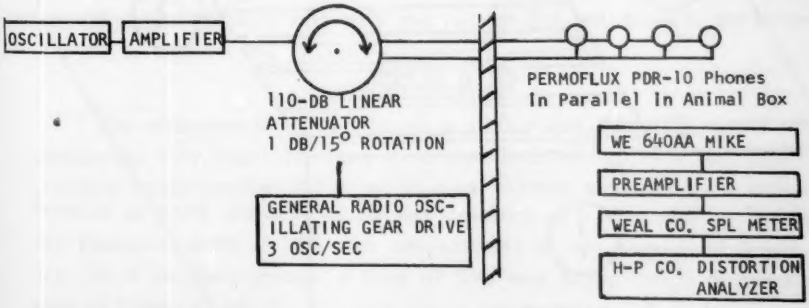


FIG. 3: APPARATUS FOR INTENSITY MODULATION

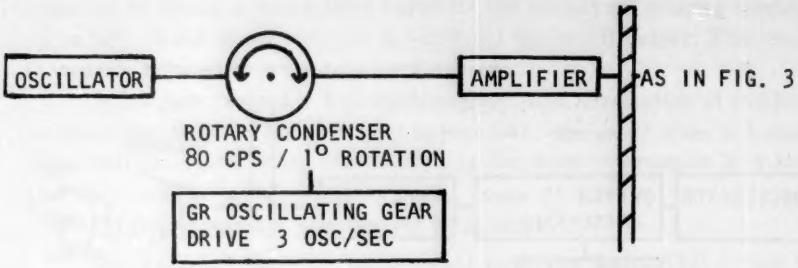


FIG. 4: APPARATUS FOR FREQUENCY MODULATION

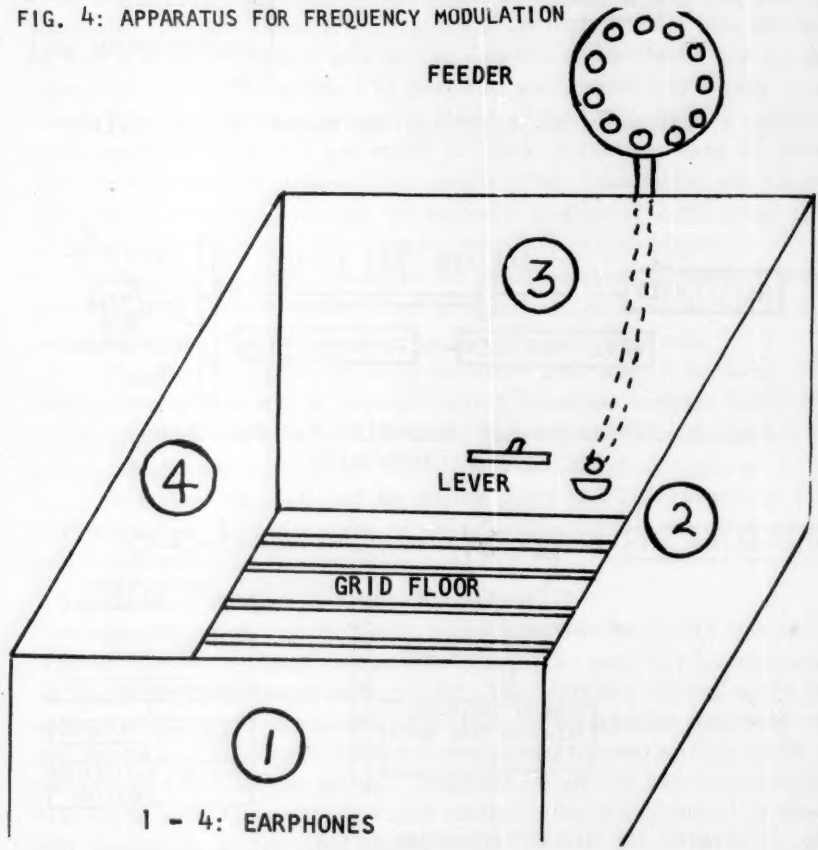


FIG. 5: RAT COMPARTMENT

bottom and a glass top was constructed locally, with a chute which would deliver a .04 rat food pellet when the rat pressed a 1-inch horizontal lever. Four phones were placed in the walls of this box. The rats were trained to press the lever when the tone was modulated, either in frequency or in intensity depending upon the group an individual rat was placed in, and to refrain from pressing the lever when the tone was steady. The animals were kept on a no–gain diet of standard chow, and were deprived at least 20 hours before each 5-minute daily session.

It was not possible, within the limitations of time and equipment available, to go to the more elaborate Bekesy-Blough two-lever procedure in which one lever reduces the extent of modulation while the other increases it; we had available neither the elaborate automatic stimulus programming equipment nor that for automatic recording of the responses indicating fluctuations around the differential threshold. However, by instituting adequate controls as outlined below we could accept as evidence of sensory discrimination any progressive change in the number of lever-pressings during modulation.

*(6) Shock Avoidance Conditioning Apparatus.*

See Fig. 5. A Foringer Co. rat operant conditioning box with associated grid power supply and shock scrambler was altered slightly to create a shuttle-box shock avoidance situation, in which upon stimulus modulation the rat had 3 sec. to go through a convenient archway to the other (uncharged) side of the grid floor. Ten trials were given at convenient times over each daily 5-min. training session. Shock strength was adjusted individually just to ensure that the rat would actually traverse the archway if he did not do so during the 3-sec. "safe" period.

One rat had to be discarded because he eventually learned to brace himself across the arch with only one foot on one rod, much in the manner of a Swiss mountaineer chimney-climbing a crevice.

X–RADIATION

The rats were taped to a board in such a way that only minute head movements were possible. They were then inserted one at a time under a standard small-hospital 250 k. v., 15 m. a. therapy unit, the 1 x 1 inch tip lowered to touch the head firmly and centered on a spot midway between the pinnae. A dose of 200r was administered in one session of 3 min. 6 sec. On some later groups, a dose of 500r was administered in one session of 7 min. 42 sec.*

* These doses were kindly calculated by Dr. Fred J. Fagan, Chief of Radiology of the Lawrence Memorial Hospital, New London, Conn., and were administered by his assistant Doris Kelly, We are deeply grateful to Dr. Fagan and his staff, and to the Hospital which offered its facilities gratis for this work.

## RESULTS AND DISCUSSION

### (1) *Pre-and Post-Exposure Audiometry by Preyer Reflex and Post-Exposure Audiometry by Cochlear Microphonics.*

Eight 3–month rats newly arrived from the supply house were studied. The average threshold SPL for the right ears is given in Fig. 6, together with the most recent data on behavioral thresholds in the same species by Blackwell and Schlossberg (1943). Their results lie intermediate between those of Eccher (1942), Gould and Morgan (1942) and Henry (1938). The slope of threshold SPL vs frequency in our rats is almost exactly that of the earlier experimenters with the exception of Henry, but shifted by about 60 db. (Some reasons for the divergence of Henry's data were discussed adequately by Blackwell and Schlosberg.)

This figure of 60 db corresponds fairly closely to the level above absolute threshold intensity which evokes some of the earlier aspects of the startle reflex in man.

These 8 untrained rats were irradiated with 200r as described above following which observations of the pinna reflex were made about 2 weeks later, and on 6 of which 1 $\mu v$ cochleograms were collected at intervals from 1–2 months later. There was no change at all in gross behavior, eating habits, or weight over these periods. The audiogram by pinna reflex showed no average change or individual trends.

The average 1 $\mu v$ cochleogram for 3 fresh rats is seen in Fig. 6 lying about 25 db louder than the behavioral thresholds of Blackwell and Schlosberg. The average post-exposure cochleogram of the 8 200r rats was not significantly different from this curve.

We may conclude that auditory acuity is unchanged by this level of irradiation. The questions remained, first, whether higher doses would affect the audiogram, and second, whether more complex abilities would suffer.

A group of 6 fresh rats was exposed to 500 r and watched for about 3 weeks to ascertain whether such a level would affect their eating habits and general activity level enough to interfere with a food-reward situation. It did not a pear that this was the case. Accordingly a group of 11 rats was exposed to 500 r and a month later examined by pinna reflex in both ears. The individual audiograms of these rats, with respect to their previous data, are found in Fig. 7.

A trend seems to appear for an improvement in acuity at 2 kc and possibly at 1 kc, and in one rat a definite though atypical improvement at the higher frequencies is seen. However, there is little or no change otherwise as a result of 500r.

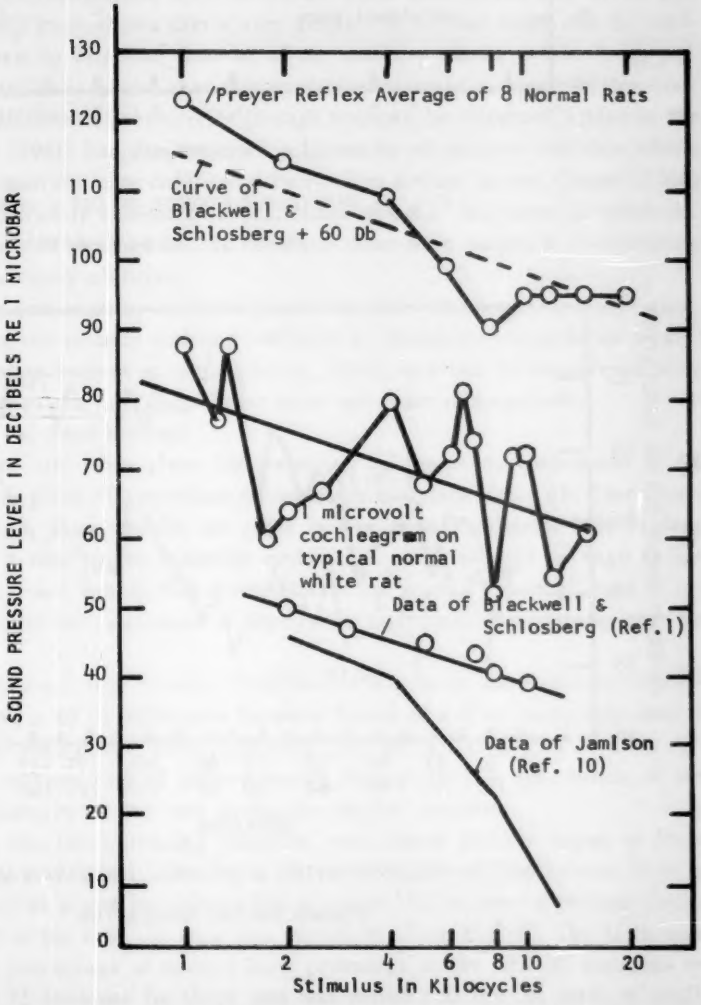


FIG. 6: AUDIOMETRIC DATA ON WHITE RATS

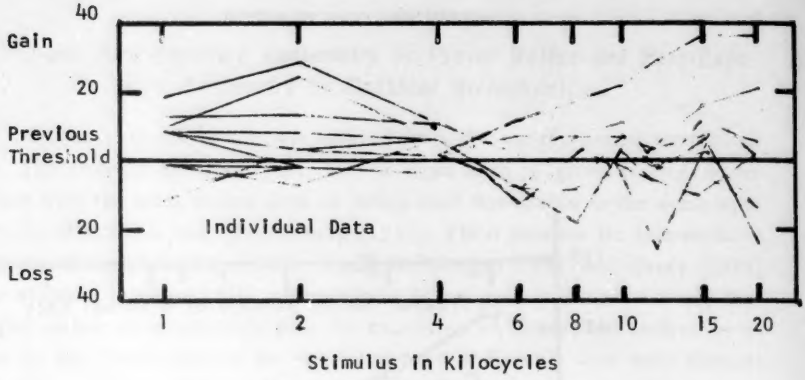


FIG. 7: NEGLIGIBLE EFFECTS OF 500 r UPON PINNA REFLEX IN 11 RATS

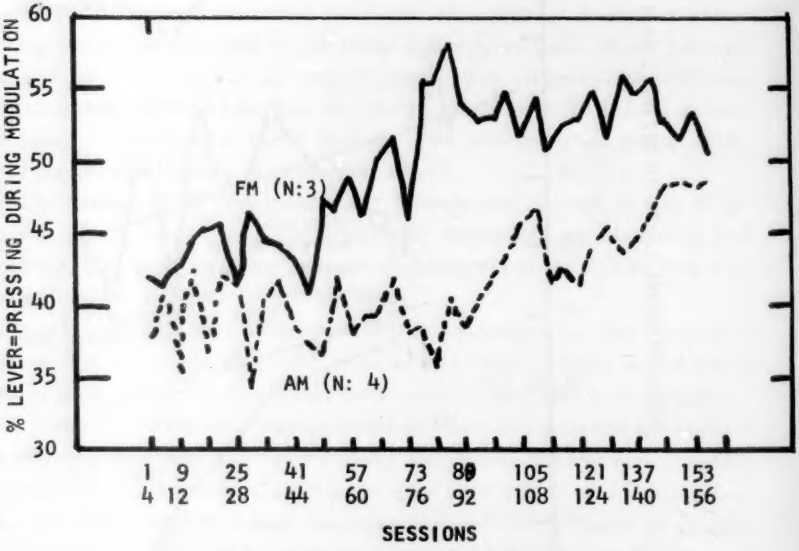


FIG. 8: ACQUISITION OF LEVER-PRESSING WITH FOOD REWARD DURING MODULATION

*(2) Changes in Auditory Sensitivity to Frequency and Intensity Modulation*

The hypothesis behind the use of these behavioral indices is that while the audiogram may be unchanged by some rather drastic neuro-physiological event, higher abilities may be deteriorated. In more advanced species this thought has been current for some time. In the cat, Kryter and Ades (1943) have shown that a very simple CR to pure tones can be unaffected even by bilateral removal of the auditory cortex, while Raab and Ades (1946) have shown that this operation destroys a more complex conditioned differential sensitivity (though this can be relearned.) Also in the cat, Neff (1951) has demonstrated a hierarchy of auditory abilities which are progressively more debilitated by cortical lesion. In man, Jerger (1960) has most recently exhibited several cases of c.n.s. disorders in which the audiogram was unaffected, but in which there were profound disturbances in other auditory abilities.

The two auditory abilities used here, pitch and loudness modulation, are among the primary auditory abilities as discovered from factor analyses of large numbers of tests (Harris, 1960), and can be considered more complex than the audiogram by at least one order of magnitude.

(a) Food–Reward

Five rats were given 100 sessions on frequency modulation at 4% and 5 were given 100 sessions on intensity modulation at 4 db. Three succumbed to a virus; results are given in Fig. 8 on 7 animals. It is evident that the 4 rats in the intensity modulation group showed no sign of improvement, and further that about 40% is the initial "chance" rate of response under the conditions of deprivation and temporal patterning that we adopted.

It is noted that Pierrel (1958) used 4 rats in an almost identical problem, using a 40 db difference between bursts of a 4 kc tone; only after 6 weeks of testing for 2 hours a day did 3 of the rats establish a stable difference between rate of lever-pressing during the 1–3 min. bursts of the louder intensity vs the rate during the weaker intensity.

In the lever-pressing situation, rats rather quickly began to learn frequency modulation, reaching a plateau after about 80 sessions. This is expressed as a rise from about 40% to about 54% in lever-pressings during that half of the time the tone was modulating (see Fig. 8). The difference in mean percentage of correct lever pressings in the first 25 sessions vs the last 25 sessions for these rats was reliable at the .01 level of confidence.

The intensity-modulation group showed no learning whatsoever, after 80 sessions, averaging about 38% correct lever-pressings, but training was nevertheless continued and a rise to about 48% was forthcoming after about 150 sessions (see Fig. 8.)

The amplitude-modulation rats are an experimental control tending to show that the rise in the learning curve of the frequency-modulation rats was in fact stimulus-controlled: This other group of quite comparable rats, under identical conditions except for the nature of the stimulus, did not parallel the rise of the frequency-modulation rats until nearly twice the number of training sessions had elapsed.

No comparable control group was arranged in this experiment to show whether the later rise in the acquisition curve of the amplitude-modulation rats was entirely or at least predominantly stimulus-controlled. It is possible that some of the rise was caused by rats finally learning to inhibit lever-pressing, and to press oftener following a successful pressing. A control procedure was instituted in which a few rats in each group which had just reached a plateau in the acquisition curve were alternately given the other type of modulation in the same temporal pattern. Fig. 9 shows the results comparing a series of 20 trials, half one type of modulation and half the other, with a sequence of 20 trials just preceding on one type of modulation alone. The curves show that rats trained on one type of modulation do slightly but reliably poorer when switched to the other type. No difference should appear if the animals were not responsive to the stated stimulus. After 4–5 sessions the animals generalize completely within the domain of modulation and do equally well on either type of modulation.

(b) Shock–Avoidance

In the shuttlebox situation likewise, the amplitude-modulation task was more difficult to learn although comparable efficiencies could eventually be reached. Figure 10 shows a rise from nearly zero to 50% avoidance in about 35 sessions for one group of 3 frequency-modulation rats, but about 55 sessions for the amplitude modulation rats. Thus, as with the food-reward rats, 4% frequency change is somewhat less difficult to discriminate than a 4 db intensity change.

No true plateaus appear in these data, and it is likely that the shuttlebox technique could be used to explore modulation DLs at considerably finer steps than 4%-4 db at 4 kc. Such a finding puts the rats ability to discriminate modulations well within the range of the normal human ear (Harris, 1960).

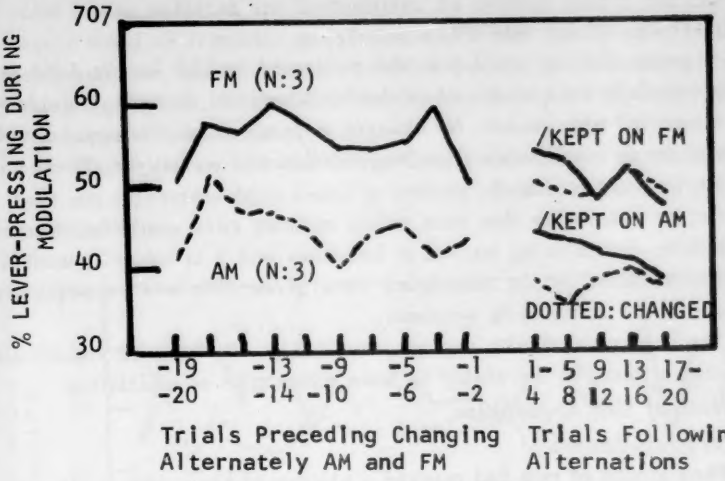


FIG. 9: SLIGHT BUT SIGNIFICANT LOSS OF PERFORMANCE WHEN TYPE OF MODULATION WAS CHANGED

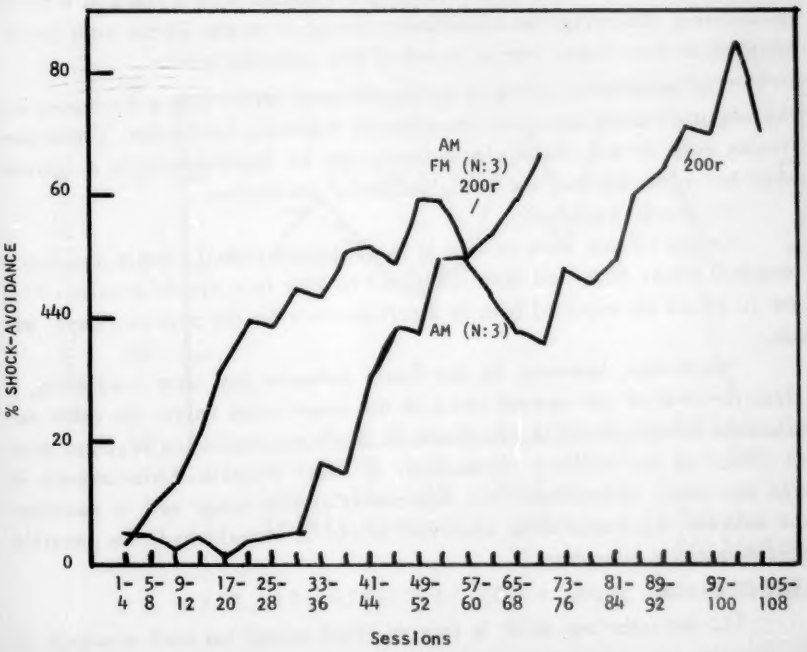


FIG. 10: LEARNING OF SHOCK-AVOIDANCE DURING MODULATION AND NEGLIGIBLE EFFECT OF 200r

*(3) Effects of 200r X–radiation.*

A group of 6 untrained rats was subjected to 200r in one dose and watched carefully for a couple of weeks for behavioral changes, especially those connected with sounds. No changes were observed that could not be accounted for on other bases. The Preyer reflex was unchanged. These animals were then dispatched.

On the possibility that more subtle auditory cues would be affected by this dose, 3 rats being trained in frequency and 3 in intensity-modulation discrimination by the shuttlebox were given 200r and subsequently continued in the usual daily sessions.

The negligible results can be seen in Fig. 10 where no significant retardation occured in the ability to learn either type of modulation.

*(4) Effects of 500r X–radiation.*

(a) Food–Reward

When groups of rats had reached a plateau of about 53% in the case of frequency modulation, and about 48% in intensity modulation, they were given 500r in a single session. Figure 11 compares for each type of modulation a block of 20 trials just preceding irradiation with a block of 6 trials immediately following. No significant change is seen. These post-irradiation trials were taken over a period of two calendar weeks.

The possibility exists of an improvement rather than a decrement for the amplitude modulation rats immediately following irradiation. These particular data do not reach significance, but an improvement in a learned skill has been reported not rarely following irradiation.

(b) Shock–Avoidance

Groups of rats were trained in the shuttlebox until correct avoidance remained above 60%, and then subjected to 500r in a single session. Figure 12 shows no especial loss in discrimination for the next two days' trials.

There was, however, by the fourth calendar day after irradiation, a clear reversal of the upward trend of the acquisition curve. No other explanation seems plausible except that at that time irradiation began to have an effect on the auditory mechanisms of these animals. Unfortunately it was necessary to terminate the experiment at this stage and to sacrifice the animals. All heads were, however, stored in formaldehyde for possible sectioning at a later date.

*(5) Discussion.*

The rat turns out to be in fact an ideal animal for such research. It is possible to train to reasonable criteria either by food–reward or by shock–avoidance techniques, using modulation ranges of an order to which

some human subjects are insensitive. An average human ear can readily detect the 4 db intensity modulation which was finally used in the work published here, but some human subjects perform at chance levels at these modulation values. We conclude that the rat is surprisingly acute at detect- either type of modulation.

There are no features of the acquisition curves shown here which have not repeatedly been found in studies of difficult learned discrimina- tions in the rat.

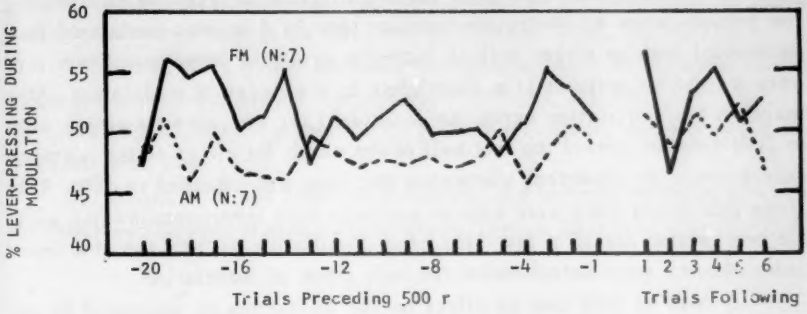


FIG. 11: EFFECT OF 500 r ON LEVER-PRESSING PERFORMANCE

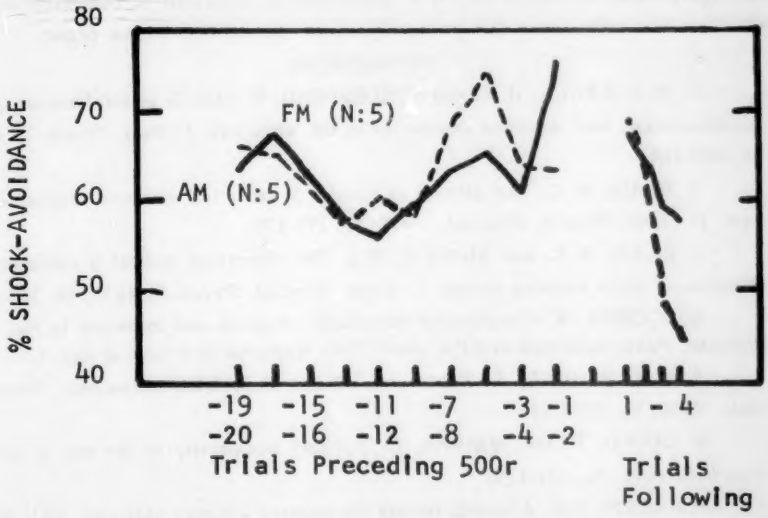


FIG. 12: EFFECT OF 500 r UPON SHOCK-AVOIDANCE

The ear appears to be rather well insulated against irradiation effects up to 500r applied as in this study. Doses of 200r in one session had no measurable effect on learning even over many weeks of observations, while during the two weeks after 500r in the food–reward rats, and four days in the shock–avoidance rats, changes in discrimination learning were confined to somewhat reduced performance in the shock–avoidance rats.

## SUMMARY

Groups of white rats were trained to press a lever for food during the periods when an otherwise constant tone of 4 kc was modulated in a sinusoidal fashion either 4 db in intensity or 4% in frequency. Other rats were trained to respond in a shuttlebox to the onset of modulation. At a stage in his acquisition curve, an individual rat was given a single dose of 200r directed toward the rear half of the skull. No effect on the learning curves could be observed, whereupon the dose was changed to 500r. Rats given this larger dose were able to maintain both lever-pressing and shuttle box habits, though a few days after X-radiation at 500r the shuttlebox habit showed some deterioration for both types of modulation.

A dose of 500r had no effect on the audiogram as measured by the Preyer pinna reflex, nor upon the 1 $\mu v$ cochleogram as compared with the average normal untreated rat. If a deterioration occurred in the shuttlebox situation the effect was not primarily on the peripheral sense organ.

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# METHOD AND MODALITY IN JUDGMENTS OF BRIEF STIMULUS DURATION

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Judgments of brief stimulus duration are typically reported to be more accurate for auditory stimuli than for visual or cutaneous. Goodfellow (10) has reported that differential discrimination of auditory duration is the most accurate and reliable, followed in order by touch and vision. This order was further indicated as consistent for three psychophysical methods. In discriminating and reproducing temporal patterns of stimuli, audition was again the most accurate, followed by vision and then touch (6). Other studies tend to confirm the apparent superiority of auditory stimulation compared to tactual or visual (11, 15).

Geldard (7) has demonstrated that mechanical vibration of the skin can be used for communication purposes. Primary cues in his system were duration, intensity, and locus of stimulation. The present writer has suggested (12) that electrical cutaneous stimulation also may be used for signaling purposes. Os can absolutely identify three or four electrical intensity levels, about the same as with mechanical vibration of the skin. Inasmuch as no data are available for duration judgments of electrical cutaneous stimuli, it would be interesting to compare such data to judgments of visual and auditory stimuli by the same Os.

Bindra and Waksburg (2) describe three methods typically used in judgments of stimulus duration: production, reproduction, and verbal estimation. The first two methods afford cues (e.g. kinesthetic or tactual) not present with the method of verbal estimation. Further, an external standard is presented when using the reproduction method, whereas judgments with other methods are presumably based solely upon physiological events and prior experience. It is possible that duration judgments in these differing situations are not based upon similar processes

Gilliand and Humphreys (8) found no difference in the magnitude of errors for the three methods, and conclude that closely related processes are involved. Gilliand, et al (9), however, indicate that the presence of an external standard with the reproduction method does not permit one to conclude that similar processes are operative when error scores are similar for the various methods.

Some investigators, however, have found differences in judged time as a function of method. Spencer (17), for example, reported that reproduction judgments were more accurate than verbal estimates, with fewer respon

ses ending in multiples of five. Clausen (4) also used the three methods for auditory and visual stimuli; his Os were schizophrenic patients. The results indicated that production and verbal estimation judgments were negatively correlated, and seemed to be dependent upon similar processes; reproduction judgments were reported to be not comparable to results with other methods .The relative reliability of judgments with the various methods also was determined by Clausen, who reported that the judgments of schizophrenic Os were least reliable when using the method of reproduction.

The present study investigated the possible interaction of method and modality, using the same Os in all conditions. Reproduction, production, and verbal estimation were used with visual, auditory, and cutaneous stimuli to assess the relative accuracy and reliability of duration judgments.

## METHOD AND PROCEDURE

Apparatus. The light source was a modified Wolf X-ray Type 300 transilluminator with a viewing window of 11 x 17 in. The window was illuminated by two 15 w. daylight fluorescent lamps controlled by an electronic dimming system. This light source provided a visual stimulus of a constant color temperature (6,000° Kelvin) which was independent of luminance. By keeping the lamp cathodes hot, instantaceous onset or offset of stimulation (for practical purposes) was permitted (3).

The auditory stimulus was the output of a General Radio Type 1390-A random noise generator presented binaurally to the O via earphones. A Hewlett-Packard Model 350B attenuator was used to control stimulus intensity.

The cutaneous stimulus consisted of a random noise signal, amplified by a McIntosh Model MC 30, presented through an active electrode of 12 mm. diameter resting on the index finger pad, and thence to an inactive electrode of 25 mm. diameter resting on the palm. Current values were computed from the reading of a Ballantine Model 320 voltmeter across a 100-ohm shunt in series with the O.

A rotary switch in series with the above circuits permitted E to control the presentation of the stimulus by means of a Hunter Model 111-C timer, or O to turn on the stimulus by means of a response switch. Judged time was recorded by a Standard Electric Model S-1A timer in parallel with the response switch.

Procedure. The electrical cutaneous RL was determined for each O at the beginning of the session. A stimulus intensity of 160% of the RL current value was used in the cutaneous sessions. The intensity of the visual or auditory stimuli used in a given session was determined by having O equate subjective intensity to the apparent intensity of the cutaneous stimulus.

Nine Os made 20 judgments of each of four stimulus durations, 0.5, 1, 2, and 4 sec., presented in a different random order for each session. The individual session utilized one method and modality, a total of nine sessions per O in a counterbalanced order of presentation.

Os made responses by the methods of production or reproduction by turning on the stimulus via the response switch; verbal estimates were given orally. Os were instructed to pay attention to stimulus duration, not switching behavior, and were told to try not to count intervals of time when the stimulus was on.

## RESULTS

The mean luminance of the visual stimulus, equated in subjective intensity to the cutaneous stimulus by the Os, was 80.9 ft-lamberts, $\sigma$ = 13.0. Mean intensity of the auditory stimulus was 18.3 db (SL), $\sigma$ =7.4.

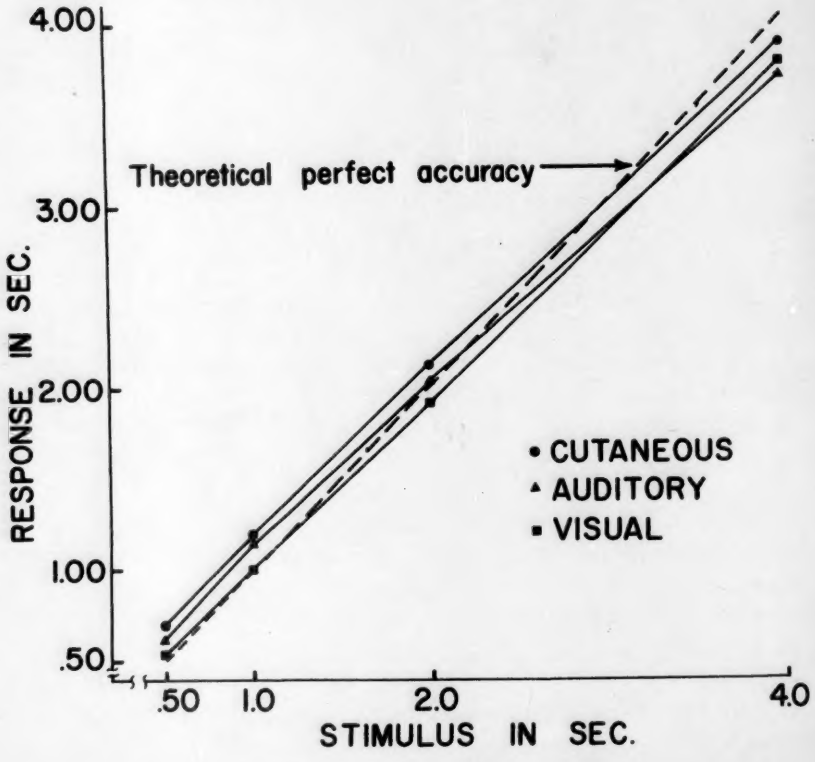


Fig. 1. Mean Response Time as a Function of Modality, 9 Os.

Mean judgments for the nine Os as a function of modality are plotted in Fig. 1. It is indicated that judged time was largest for the cutaneous stimulation at all intervals, and smallest for visual stimulation at all intervals except 4 sec. Further, there was a tendency to overestimate the shorter durations and to underestimate the longest duration.

Mean judgments as a function of method are presented for the various modalities in Figs. 2, 3, and 4. These figures indicate that judged time for a particular stimulus duration is a function of both method and modality. Verbal estimates demonstrated overestimation of all auditory intervals, and

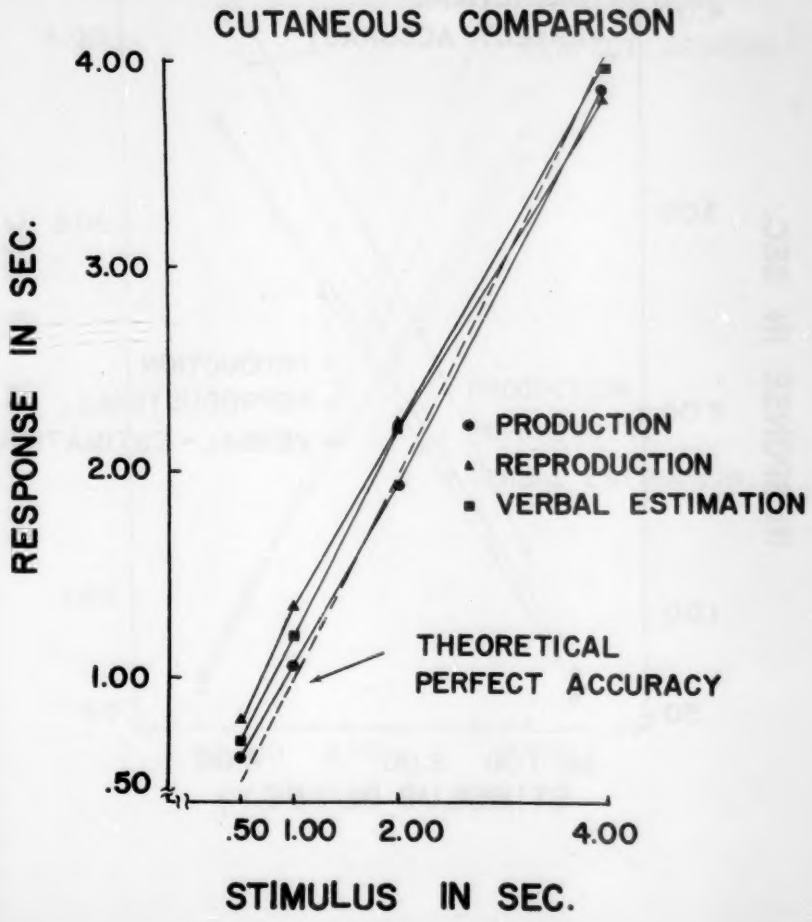


Fig. 2. Mean Judgments of Cutaneous Stimulation Duration as a Function of Method.

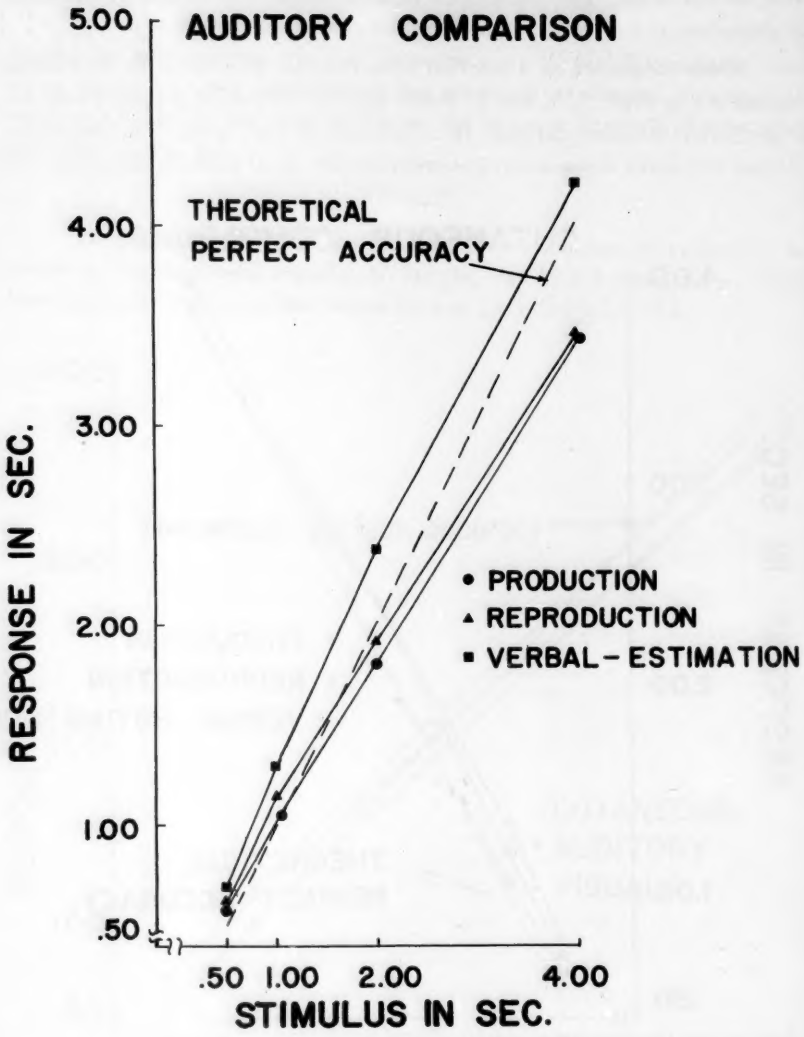


Fig. 3. Mean Judgments of Auditory Stimulus Duration as a Function of Method.

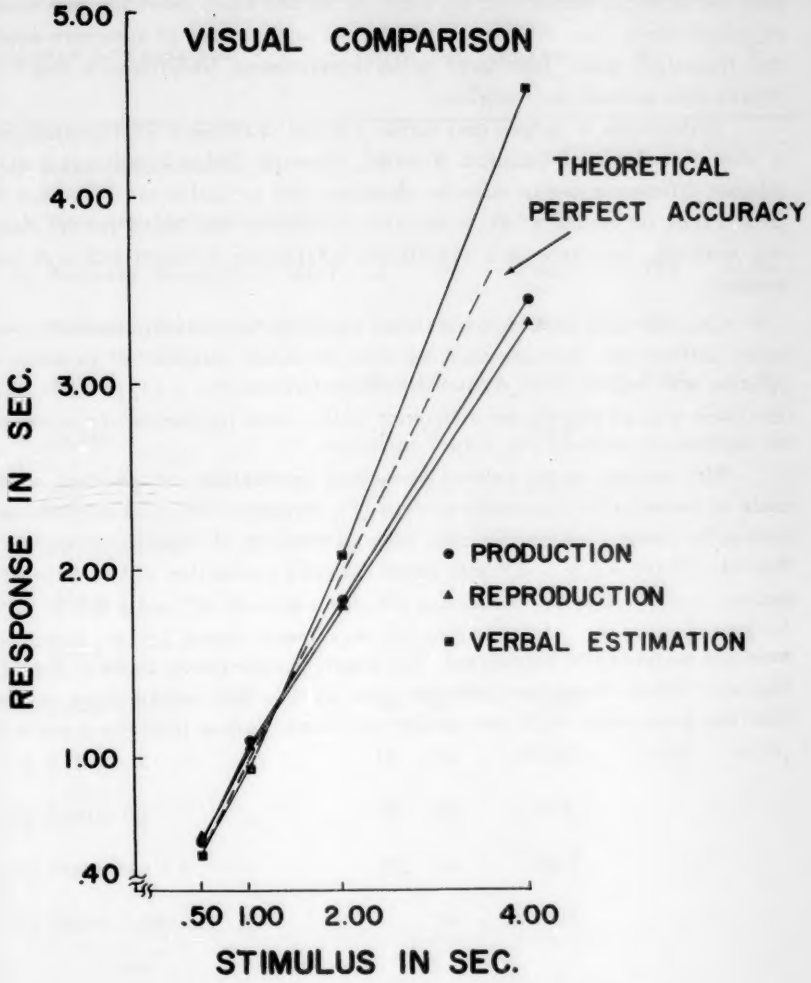


Fig. 4. Mean Judgments of Visual Stimulus Duration as a Function of Method.

underestimation of all cutaneous durations except 4 sec. Judgments with this method when using visual stimuli demonstrated underestimation of intervals below 2 sec. and overestimation of 4 sec. Production and reproduction methods with all modalities tended to result in longer judged times than the physical duration of the stimulus for the short intervals, and shorter judged times than the longer intervals. For the range of durations used, the transition point from over to underestimation (indifference interval) varies with method and modality.

Differences in judged time for the various conditions were determined by use of analysis of variance. Results, shown in Table I, indicate a significant difference due to stimulus duration, and a significant difference in judged time for modality. No significant difference was found for the various methods, but there is a significant interaction between subjects and method.

Critical ratio tests for correlated samples were used to evaluate modality differences. Results indicate that the mean judgment of cutaneous duration was significantly greater than that of visual ($t = 2.43$, $p < .05$), and that there was no significant difference in the mean judgments of cutaneous vs. auditory or auditory vs. visual durations.

With respect to the subject by method interaction, comparisons were made of the relative magnitude of each O's response with each method, and rank-order correlation coefficients were determined. A significant negative Rho of -.78 ($df = 7$, $p < .05$) was found between production and verbal estimation. Reproduction vs. production yielded a Rho of .42, and a Rho of -.08 for reproduction vs. verbal estimation was found; these values, however, were not statistically significant. The negative correlation between production and verbal estimation indicates that Os who had judged times higher than the group mean with one method had lower values than the mean with

TABLE I

ANALYSIS OF VARIANCE OF RESPONSE TIME

| Source of Variation | Error Term | df | Mean Square | F | P |
|---|---|---|---|---|---|
| 1) Between Subjects (S) | 5 | 8 | 1.3575 | | |
| 2) Between Methods (Me) | 5 | 2 | 2.4476 | | |
| 3) Between Modalities (Mo) | 17 | 2 | .7362 | 3.1155 | <.05 |
| 4) Between Intervals (I) | 12 | 3 | 156.4952 | 178.8107 | <.01 |
| 5) SxMe | 12 | 16 | 4.4608 | 5.0968 | <.01 |
| 6) SxMo | 16 | 16 | .2653 | | |
| 7) SxI | 12 | 24 | .2932 | | |
| 8) Me x Mo | 12 | 4 | .4438 | | |
| 9) Me x I | 12 | 6 | .9722 | | |
| 10) Mo x I | 12 | 6 | .0846 | | |
| 11) SxMe x Mo | 15 | 32 | .3284 | | |
| 12) SxMe x I | 15 | 48 | .8752 | 3.6345 | <.01 |
| 13) SxMo x I | 15 | 48 | .1278 | | |
| 14) Me x Mo x I | 15 | 12 | .2327 | | |
| 15) SxMe x Mo x I | | 96 | .2408 | | |
| Total | | 323 | | | |
| Pooled Interactions | | | | | |
| 16) (15 + 13 + 11) | | 176 | .2259 | | |
| 17) (15 + 13 + 11 + 7 + 6) | | 216 | .2363 | | |

the other method. The inverse relationship between production and verbal estimation accounts for much of the subject by method interaction.

The relative reliability of performance with each method and modality was determined by correlation of the mean odd-even judgments of the Os. These values, shown in Table II, in general were high for all methods and modalities. Further, there was no consistent trend for low reliability to be associated with a particular method or modality.

TABLE II

RELIABILITY COEFFICIENTS (ODD-EVEN SPLIT) FOR EACH METHOD & MODALITY

| | | 1/2 | 1 | 2 | 4 |
|---|---|---|---|---|---|
| Production | Audition | .94 | .96 | .97 | .99 |
| | Cutaneous | .72 | .76 | .98 | .98 |
| | Vision | .98 | .99 | .98 | .98 |
| Reproduction | Audition | .95 | .85 | .87 | .95 |
| | Cutaneous | .94 | .47 | .92 | .89 |
| | Vision | .87 | .79 | .89 | .94 |
| Verbal - Estimation | Audition | .96 | .99 | .99 | .96 |
| | Cutaneous | .98 | .83 | .98 | .98 |
| | Vision | .88 | .88 | .90 | 1.00 |

## DISCUSSION

High reliability of duration judgments was found for the three modalities of this study, consistent with other data (11). Inasmuch as judgments of cutaneous duration were of about the same order of magnitude as auditory judgments[1], and were as reliable as either auditory or visual judgments, it may be concluded that the use of duration as a cue in an electrical cutaneous communication system is quite feasible.

The failure to find significant differences between judgments of auditory and visual durations in this study may have been due to the experimencal conditions employed. Behar (1), for example, has indicated that these differences may be obscured when using methods affording kinesthetic cues. The subjectively longer auditory than visual second found by Behar with a category-scale technique was not evidenced in data reported by Hirsh, et al (13), who found no audio-visual differences with the method of reproduction. The stimuli in the present study, white light and white noise (each equated for subjective intensity to the cutaneous stimulus), may also have tended to reduce these differences. Studies which have reported differences between judgments of auditory vs. cutaneous duration have used as the stimulus mechanical vibration of the skin, whereas the present study utilized a random frequency electrical signal applied to the finger.

Lack of significant differences due to method in the present investigation, and similar results by Gilliand and Humphreys (8), seem to indicate that reproduction, production and verbal estimation yield similar data (in terms of judged time) upon direct comparison. Although Clausen (4) reported low reliability for the method of reproduction for schizophrenic Os, he notes that similar results will not necessarily be found for normal Os. Differences in temporal experience between normal and pathological groups have been reported (5, 14, 16). Autism and the inability to maintain a mental set, characteristic of schizophrenia, may have maximal influence upon temporal judgments with the method of reproduction, which requires O first to attend to a stimulus and then to reproduce his perception of the stimulus.

[1] Auditory duration judgments by the method of reproduction were nearly identical to the results of the present study in a situation wherein Os were given adequate vestibular stimulation in addition to auditory stimuli. Temporal perception, therefore, may be relatively unaffected by extraneous stimulation. Collins, W. E. Further studies of the effect of mental set upon vestibular nystagmus. USA Med. Res. Lab. Rep. No. 443, 1960.

Clausen also pointed out that production and verbal estimation seem to be measuring the relationship of subjective and physical duration, whereas reproduction may be dependent upon a different process. The significant subject by method interaction of the present experiment, the significant rank-order correlation of the production and verbal estimation judgments, and the lack of significant correlation of reproduction judgments with those of other methods, are not inconsistent with Clausen's hypothesis.

The present data indicate that most durations were overestimated by the Os. Further, production judgments indicate that subjective time appears to be slower than physical time for the shorter durations of the present study and faster than physical time with the longest stimulus duration, i.e. judged time was greater than physical time for the shorter durations and shorter for the 4 sec. stimulus. In a recent review, Wallace and Rabin (18) point out the general tendency to overestimate short intervals and to underestimate long ones with these methods.

In the present experiment, the transition point from longer to shorter judged time than the physical duration (i.e. the indifference interval) varied from 1.26 to 3.60 sec., dependent upon method and modality. These values are somewhat greater than the .6 sec. value found by Woodrow (19), but are within the range of .36 to 5.0 sec. reported in his review. The present data, therefore, appear to be consistent with the tendency indicated by Woodrow; the indifference interval seems to be a function of the stimulus situation.

## SUMMARY

Relative accuracy and reliability of duration judgments were investigated for auditory, visual and electrical cutaneous stimuli. Methods of production, verbal estimation, and reproduction were used, with stimulus durations of 0.5 to 4.0 sec.

Significant differences in judged time were found for modality and interval. Critical ratio tests indicated that auditory judgments did not differ from those based on visual or cutaneous stimuli. The latter two, however, were significantly different from one another. High reliability of judgments was found for all methods and modalities.

Method differences reported in other studies were not apparent upon direct comparison using normal Os, confirming a similar finding reported by Gilliland and Humphreys. It is concluded that the use of duration as a cue in an electrical cutaneous communication system is feasible.

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# 145 RECRUITMENT AND ALLIED PHENOMENA IN DIFFERENTIAL DIAGNOSIS

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Much confusion about recruitment and recruitment 'tests' derives from the fact that most people are consistently talking about the wrong thing. For too long, thinking in this area has been conditioned by a very misleading oversimplification, 'Is recruitment present or absent?'

A more meaningful question would be, 'What are the various aberrant phenomena associated with lesions at different sites within the auditory mechanism, and how may they be used to identify or predict site of lesion?'

Unfortunately, preoccupation with recruitment has had an extremely stifling and repressive effect on research in this area. Many investigators have erred by making the totally unwarranted assumption that recruitment was the necessary and proper criterion against which to validate all other phenomena. Others have simply denied the relevance of all other phenomena, apparently assuming that, with the discovery of the recruitment phenomenon all knowledge was complete.

The present dilemma had its inception in the now-classic report by Dix, Hallpike and Hood (1) that loudness recruitment (as measured by the alternate binaural loudness balance test) was characteristically present in labyrinthine disorders, such as Meniere's Disease, but characteristically absent, or only partial, in retro-labyrinthine disorders, such as acoustic tumors.

In view of the potential value of this finding in determining site of lesion within the auditory system, many investigators sought alternative methods for the detection and/or measurement of recruitment, methods not limited (as is the alternate binaural loudness balance test) to unilateral loss. The ensuing years have witnessed the development of many proposed

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techniques purporting to measure recruitment indirectly and a like number of counter claims to the effect that the tests have not proven themselves as indirect measures of recruitment either for theoretical reasons or because they do not agree with the alternate binaural loudness balance test.

Throughout the flurry of claims and denials some investigators have apparently lost sight of two fundamental considerations:

1. The primary issue is not 'recruitment' but site of lesion. If recruitment tests (i.e., alternate binaural and monaural bifrequency loudness balance tests) assist in this task they should by all means be used. And in like manner, if other phenomena assist in this task they should be used also. But one should not be seduced into the erroneous belief that the measurement of recruitment is the primary goal and that any other test is good or bad only to the extent that it agrees with the loudness balance test.

2. In spite of a rather pervasive lack of reticence to cast aspersions on other tests, no one has thought to ask, 'How good is the loudness balance test?'

The following data bear upon these important questions.

For the past three years we have administered an extensive battery of auditory tests to all patients with unilateral loss. The present report is based on 129 such patients. In addition to routine pure tone and speech audiometry, each patient was given the alternate binaural loudness balance test, the SISI test, and Bekesy audiometry.

Our method for administering the alternate binaural loudness balance test (ABLB) differs from that of most previous workers in a number of important aspects. Exact details of instrumentation and procedure are given in Jerger and Harford (2).

The SISI test measures the patient's ability to hear small, short changes in sound intensity. Twenty 1-db increments of 200 msec duration are superimposed on a steady-state tone at 5-sec intervals. The level of the steady tone is fixed at 20 db above the patient's threshold. The patient responds each time he hears a change in this steady tone. His test score is the percentage of correct responses to the series of 20 increments. We consider scores above 55% to be positive (i.e., indicative of abnormally keen differential intensity sensitivity), between 20 and 55% questionable, and below 20% negative. Exact details of instrumentation and procedure are given in Jerger, Harford and Shedd (3).

Our interpretation of Bekesy audiometry is based on the relationship between tracings of continuous (C) and periodically interrupted (I) stimuli in the same ear. We distinguish four types of relationship. In type I tracings C and I interweave and the tracing width is about 10 db. In type II, tracing C drops below I between 500 and 1000 cps and remains 10–20 db

below I through the high-frequency range. The width of the C tracing ordinarily becomes quite small after C drops below I. The type III pattern is quite dramatic. C drops below I to an astonishing degree, even at very low frequencies. The C width, however, remains normal (i.e., about 10 db).Ir Type IIII tracings, C runs below I across the entire frequency range but does not show the dramatic drop characterizing the type III tracings. Exact details of instrumentation and procedure are given in Jerger (4).

Tables 1, 2, and 3 show results obtained with this three-test battery in 52 cases with relatively well-defined sites of lesion. Included in this group are 21 patients with unilateral conductive loss, 20 patients with medically-diagnosed Meniere's Disease, and 11 patients with surgically-confirmed acoustic neuronoma.

Table 1 shows the distribution of all test results on the 21 patients with conductive loss. Note that the majority (14) have no recruitment, with negative SISI, and type I Bekesy. There are, however, exceptions. Five have either questionable or positive SISI and two have type II tracings.

Table 2 shows the distribution of test results in 20 cases of Meniere's Disease. All 20 had positive SISI scores, 19 had type II Bekesy, but only 10 had complete recruitment. Five had partial recruitment and five had no recruitment at all.

Table 3 shows the distribution of test results in 11 cases of acoustic neuronoma. All 11 have either type III or type IIII Bekesy tracings. Ten had negative SISI scores and, in one, results were questionable. Nine had no recruitment, but in two, there was partial recruitment.

Table 4 shows the distribution of test results in 75 patients with unilateral sensorineural loss of unknown etiology. Note the rather poor correlation between the ABLB test and either of the other two tests. Fifty-four of the 75 patients have type II Bekesy tracings, 58 have positive SISI scores, but only 16 have complete recruitment and 22 partial recruitment. Thirty seven show no recruitment at all. *Type 2 Bekesy tracings and positive SISI scores occur with about equal frequency whether recruitment is complete, partial, or absent.* Clearly, neither Bekesy nor SISI is a very good predictor of recruitment.

The astonishing lack of agreement among these tests is susceptible of many interpretations. Some investigators would simply reject the Bekesy and SISI tests as worthless since they do not predict the presence or absence of recruitment, and they surely do not. To those who are interested in recruitment *qua* recruitment this is certainly a reasonable interpretation, but to those whose primary interest is site of lesion, a more meaningful question would be, 'Which test predicts site of lesion?' Table 5 gives the answer. Here are plotted the original 52 cases with relatively well defined

sites of lesion, showing the number of patients at each site for each possible test outcome. One notes, for example, that complete recruitment occurred only in Meniere's patients, partial recruitment occurred in both Meniere's and acoustic neuronoma patients, and in all three groups there were cases in which no recruitment occurred. Type I and type II Bekesy tracings occurred in both conductive and Meniere's patients, but types III and IIII occurred only in acoustic neuronoma. Positive SISI scores occurred in both conductive and Meniere's groups, questionable and negative SISIs in both conductive and acoustic neuronoma groups. If one adopted the simple rule that, for each individual test, one would predict site of lesion according to the group showing the largest number of patients for a particular test outcome, then the ABLB test would misclassify 16 patients, SISI would misclassify 13 patients and Bekesy audiometry would misclassify 3 patients. The answer to the original question, 'Which test predicts site of lesion?' is clear. None of them does. They are all less than perfect. The ABLB test is, in fact, the poorest predictor.

One can, however, improve one's prediction considerably simply by taking advantage of all the available information. If, for example, one predicts site of lesion on the joint outcome of any two of these three tests, the situation improves remarkably. A combination of ABLB and SISI (Table 6) would misclassity 11 cases, ABLB and Bekesy (Table 7) would misclassify two cases, and Bekesy and SISI (Table 8) would misclassify only one case. Finally, if one bases one's prediction on the outcome of all three tests (Table 9) re-classification is perfect. Each site of lesion is characterized by a group of joint outcomes distinct from that of any other site. In other words, any one of these three tests, by itself, is imperfect. A combination of two tests, properly selected, improves prediction considerably, and prediction based on all three tests appears to be quite accurate.

According to the present data, the best single test is Bekesy audiometry, and the best combination of two tests is Bekesy and SISI. At first glance the ABLB test would appear to contribute exceedingly little to the total problem. We believe, however, that to abandon ABLB would be to make the same mistake as those who would reject other tests because they do not agree with ABLB. What needs to be stressed is the paradoxical situation that no single test, by itself, is infallible, but that, in combination with other tests, it can become a powerful tool. As a result of our experiences with this multiple test battery we have become increasingly distrustful of the outcome of any single test, but increasingly confident of the significance one may attach to the overall pattern of test results from a properly chosen battery.

TABLE 1. Distribution of Bekesy, SISI, and Recruitment (ABLB) test results in 21 cases of unilateral conductive loss.

| Bekesy Type | No Recruitment (ABLB-N) | | | Partial Recruitment (ABLB-P) | | | Complete Recruitment (ABLB-C) | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | SISI | | | SISI | | | SISI | | | |
| | - | ? | + | - | ? | + | - | ? | + | |
| I | 16 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 19 |
| II | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| III | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 15 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 21 |

TABLE 2. Distribution of Bekesy, SISI, and Recruitment (ABLB) test results in 20 cases of unilateral Meniere's Disease.

| Bekesy Type | No Recruitment (ABLB-N) | | | Partial Recruitment (ABLB-P) | | | Complete Recruitment (ABLB-C) | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | SISI | | | SISI | | | SISI | | | |
| | - | ? | + | - | ? | + | - | ? | + | |
| I | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| II | 0 | 0 | 5 | 0 | 0 | 4 | 0 | 0 | 10 | 19 |
| III | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 0 | 0 | 5 | 0 | 0 | 5 | 0 | 0 | 10 | 20 |

TABLE 3. Distribution of Bekesy, SISI, and Recruitment (ABLB) test results in 11 cases of acoustic neuromas.

| Bekesy Type | No Recruitment (ABLB-N) | | | Partial Recruitment (ABLB-P) | | | Complete Recruitment (ABLB-C) | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | SISI | | | SISI | | | SISI | | | |
| | - | ? | + | - | ? | + | - | ? | + | |
| I | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| II | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| III | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| IV | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 4 |
| Total | 9 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 11 |

TABLE 4. Distribution of Bekesy, SISI, and Recruitment (ABLB) test results in 75 cases of unilateral sensorineural loss of unknown etiology.

| Bekesy Type | No Recruitment (ABLB-N) | | | Partial Recruitment (ABLB-P) | | | Complete Recruitment (ABLB-C) | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | SISI | | | SISI | | | SISI | | | |
| | - | ? | + | - | ? | + | - | ? | + | |
| I | 1 | 0 | 2 | 1 | 1 | 1 | 0 | 0 | 2 | 9 |
| II | 2 | 2 | 26 | 2 | 2 | 10 | 1 | 2 | 9 | 56 |
| III | 2 | 0 | 2 | 0 | 1 | 1 | 0 | 0 | 1 | 7 |
| IV | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 5 |
| Total | 5 | 2 | 30 | 3 | 4 | 13 | 1 | 2 | 13 | 75 |

TABLE 5. Distribution of Bekesy, SISI, and Recruitment (ABLB) test results of the 52 cases summarized in Tables 1, 2, and 3, classified according to presumed site of lesion.

| Test | | Site of Lesion | | |
|---|---|---|---|---|
| | | Middle Ear | Cochlea | VIIIth Nerve |
| ABLB | C | 0 | 10 | 0 |
| | P | 0 | 5 | 1 |
| | N | 21 | 3 | 7 |
| Bekesy | I | 19 | 1 | 0 |
| | II | 2 | 19 | 0 |
| | III | 0 | 0 | 7 |
| | IV | 0 | 0 | 4 |
| SISI | + | 1 | 20 | 0 |
| | ? | 4 | 0 | 1 |
| | - | 15 | 0 | 10 |

TABLE 6. Joint outcome of Recruitment (ABLB) and SISI tests, classified according to presumed site of lesion, in the 52 cases of Tables 1, 2, and 3.

| ABLB | SISI | Middle Ear | Cochlea | VIIIth Nerve |
|---|---|---|---|---|
| C | - | 0 | 0 | 0 |
| C | ? | 0 | 0 | 0 |
| C | + | 0 | 10 | 0 |
| P | - | 0 | 0 | 1 |
| P | ? | 0 | 0 | 1 |
| P | + | 0 | 1 | 0 |
| M | - | 11 | 0 | 9 |
| M | ? | 4 | 0 | 0 |
| M | + | 2 | 1 | 0 |

TABLE 7. Joint outcome of Recruitment (ABLB) and Bekesy tests, classified according to presumed site of lesion, in the 52 cases of Tables 1, 2, and 3.

| ABLB | Bekesy-type | Middle Ear | Cochlea | VIIIth Nerve |
|---|---|---|---|---|
| C | I | 0 | 0 | 0 |
| C | II | 0 | 10 | 0 |
| C | III | 0 | 0 | 0 |
| C | IV | 0 | 0 | 0 |
| P | I | 0 | 1 | 0 |
| P | II | 0 | 1 | 0 |
| P | III | 0 | 0 | 0 |
| P | IV | 0 | 0 | 2 |
| M | I | 13 | 0 | 0 |
| M | II | 3 | 1 | 0 |
| M | III | 0 | 0 | 7 |
| M | IV | 0 | 0 | 2 |

TABLE 8. Joint outcome of Bekesy and SISI tests, classified according to presumed site of lesion, in the 52 cases of Tables 1, 2, and 3.

| Bekesy-type | SISI | Middle Ear | Cochlea | VIIIth Nerve |
|---|---|---|---|---|
| I | + | 2 | 1 | 0 |
| I | ? | 3 | 0 | 0 |
| I | - | 14 | 0 | 0 |
| II | + | 0 | 10 | 0 |
| II | ? | 1 | 0 | 0 |
| II | - | 1 | 0 | 0 |
| III | + | 0 | 0 | 0 |
| III | ? | 0 | 0 | 0 |
| III | - | 0 | 0 | 7 |
| IV | + | 0 | 0 | 0 |
| IV | ? | 0 | 0 | 1 |
| IV | - | 0 | 0 | 3 |

TABLE 9. Joint outcome of Bekesy, SISI, and Recruitment (ABLB) tests, classified according to presumed site of lesion, in the 52 cases of Tables 1, 2, and 3. (Non-occurring joint outcomes not listed.)

| Bekesy-type | SISI | ABLB | Middle Ear | Cochlea | VIIIth Nerve |
|---|---|---|---|---|---|
| I | - | M | 11 | 0 | 0 |
| I | ? | M | 3 | 0 | 0 |
| I | + | M | 2 | 0 | 0 |
| II | - | M | 1 | 0 | 0 |
| II | ? | M | 1 | 0 | 0 |
| I | + | P | 0 | 1 | 0 |
| II | + | M | 0 | 1 | 0 |
| II | + | P | 0 | 1 | 0 |
| II | + | C | 0 | 10 | 0 |
| III | - | M | 0 | 0 | 7 |
| IV | - | M | 0 | 0 | 2 |
| IV | - | P | 0 | 0 | 1 |
| IV | ? | P | 0 | 0 | 1 |

## SUMMARY

From the standpoint of differential diagnosis the important consideration is not recruitment but site of lesion. Recruitment tests (i.e., loudness balance methods) are of value to the extent that they predict site of lesion successfully. The most meaningful criterion to apply to other tests involving other phenomena is not whether they predict recruitment but whether they predict site of lesion. If they do, then they are of value whether they predict recruitment or not.

The present study compared three procedures; a recruitment test (ABLB), Bekesy audiometry, and a test of differential intensity sensitivity (SISI), with respect to their ability to predict site of lesion.

The best single predictor was Bekesy audiometry. The worst single predictor was the recruitment test.

Prediction was improved substantially by considering the joint outcome of all three tests.


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# RELATIVE INTELLIGIBILITY OF ITEMS ON CID AUDITORY TEST W-1

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The 36 spondaic items of CID Auditory Test W-1 were administered to 24 untrained normal-hearing subjects for the purpose of estimating the range of intelligibility characterizing this test. The range computed from data produced by these subjects was found to be 10 db, which is considered to be unduly wide and detrimental to the precision of the test. Present results have led to the conclusion that the precision of auditory speech threshold measurements may be enhanced through the use of an indicated group of 22 words exhibiting a range of only 3.5 db.

Current methods for determining the auditory threshold for speech have their origin in work carried out at the Bell Telephone Laboratories in the late 1940's. BTL investigators appreciated the potential usefulness of word lists of homogeneous audibility in measuring the efficiency of sound transmission equipment, and conducted studies designed to discover the relative homogeneity of different classes of speech stimuli. These experiments disclosed that the greatest homogeneity was exhibited by disyllabic words spoken in a spondaic stress pattern. Such words have been termed 'spondees.' Egan (3, p. 965) reported that:

> Word lists assembled from spondees have proved particularly useful in tests whose purpose is to establish accurately the level at which speech can just be heard. These homogeneous words reach the threshold of hearing, all within a narrow range of intensity, and thereby serve to determine with precision the threshold of hearing for speech.

From the measurement of the efficiency of communication equipment, it was but a step to the use of spondees for measurement of the efficiency of the auditory apparatus. Hudgins et al (5) made phonographic recordings of two lists of 42 spondees each, and employed them in clinical determinations of the auditory threshold for speech. Each of these tests, designated PAL Auditory Test No. 9, comprised seven groups of six words each, successive groups being recorded at progressively descending intensities 4 db apart. Threshold intensity was taken to be that level at which the listener correctly heard 50% of the words.

Hirsh et al (4) and Benson et al (1) later reported the development of a new recorded test including only 36 of the 84 words found in Auditory

Test No. 9. The new test was recorded in both constant level (CID Auditory Test W-1) and descending level (CID Auditory Test W-2) versions, and presumed to be superior to Auditory Test No. 9 in homogeneity of the items. The CID series is presently the most widely used instrument for determining the threshold for speech.

Although it is reasonably certain that spondees are more homogeneous than, for example, monosyllables or nonsense syllables, it is suggested that the degree of homogeneity observed in past experiments was probably largely due to the use of only trained listeners. This conclusion stems from observations of the application of CID tests to normal-hearing clinical patients, upon whom definite differences in intelligibility of the test items appear. This is to say that certain items tend to be consistently more intelligible or less intelligible than others, and thus adversely influence the precision of the test.

If these observations reflect genuine heterogeneity in W-1, then their importance is evident both for the clinician and for those concerned with establishing an improved standard difference between auditory thresholds for speech and for a 1000 cps pure-tone (2, 6). Therefore, the present study was undertaken to estimate the range of intelligibility of the 36 items of CID Auditory Test W-1, in order to provide a basis for further increasing its precision.

## PROCEDURE

A 33 1/3 rpm disc-recording of CID Auditory Test W-1, Lists E and F, was transferred to magnetic tape using a Presto record player and a Magnecord M-80 tape-recorder. From this master tape three additional randomizations of List E and three of List F were made, yielding a total of eight equated test tapes.

Twenty-four subjects were selected on the basis of two criteria: (a) at least one ear with pure-tone thresholds better than 10 db for each measured frequency from 250 cps to 4000 cps, and (b) previous unfamiliarity with auditory tests in general. The first criterion was invoked to minimize the influence of frequency-selective factors; the second, to cause the experimental group to resemble, at least in this one way, the type of population to which the tests in question are usually administered. There were twenty male and four female subjects, outpatients and employees from the VA West Side Hospital, ranging in age from 20 to 53 years, with an average age of 36 years.

During experimental runs, the test tapes were played on a Berlant Series 30 tape recorder and fed thru a Grason-Stadler model 162 Speech Audiometer to TDH-39 earphones. The subject was given an instruction sheet which he was asked to follow visually while the tester read aloud:

> You are to sit quietly and listen carefully for a man's voice to come on in your left (right) ear. The man will be telling you to 'Say the word _____,' and that is exactly what I want you to do. Say aloud the word which he tells you to say. If he says, 'Say the word dog,' then you say, 'dog.' If he says 'Say the word man,' then you say, 'man.' Sometimes a word will be so soft that you will not understand it; you don't have to tell me that it was too soft for you. Just sit quietly and listen for the next word. Other times the words will be loud enough to hear clearly. Remember to sit quietly and listen carefully. Don't expect to get all of the words, but try to get as many words right as you can. Are there any questions?

Following any necessary clarification of instructions, the subject was told to relax until he heard the speaker say 'Are you ready?' The attenuator was set at -10 db HL during preliminary calibration and, just prior to the 'ready' phrase, was raised to 35 db HL to alert the subject. Following this phrase, the gain was set to the initial test level of -4 db HL. A complete set of 36 words was run at -4 db HL, which was chosen to yield 0% identification. A different randomization was presented at 0 db HL, still another at 4 db HL, and so on, with successive lists being presented at 4 db increments. The eight test levels, then, were: -4, 0, 4, 8, 12, 16, 20, and 24 db re average normal threshold for speech. During each run, correct responses were noted on a scoring form by the tester. When 100% identification was achieved, regardless of the level at which this occurred, the experimental session was terminated.

The ascending mode of presentation, mentioned above, was employed to maintain the subject's lack of familiarity with the test items until he actually perceived enough auditory clues to lead to correct identification.

Because only the relative intelligibility of the W-1 items was of direct interest in this study, intensity in db relative to average normal threshold was converted to Sensation Level. This minimized the influence of inter-subject threshold differences by allowing each subject to serve as his own control. This, when a subject first correctly identified an item, the Hearing Level then being used was taken as his 0 db SL, and every word which he correctly identified at that level was so scored. Words he correctly identified for the first time at the next higher level (4 db increment) were then given a score of 4 db SL, and so on, until 100% correct identification had been attained. In this way, words of equal subjective intelligibility were weighted equally and independently of existing inter-subject threshold disparities.

## RESULTS AND DISCUSSION

The results of this study are summarized in Table I, which shows the relative intelligibility of the items as indicated by the mean sensation level at which first correct identification occurred. The range extends from 2.7 db (workshop) to 12.7 db (hothouse). This means that an average member of this group first correctly identified the word workshop at a level 10 db less intense than that at which he was first able to identify the word hothouse. This range is here considered to be unduly wide. But, it is believed that the controls exerted in this investigation were such that the usual confounding factors were minimized and thus permitted such inter-item differences to show up. The ears tested were normal to eliminate frequency-selective factors; all subjects had a common lack of familiarity with the words as test items, though their familiarity with them as linguistic units probably varied; presentations were randomized to preclude order effects; the recorded words all monitored at approximately the same place on a VU meter, and an ascending method of presentation was used to ensure that a correct response was based on auditory clues alone.

At present, there appears to be no basis for a direct referral of these data to clinical experience, for it has become a general practice to administer W-1 via monitored live-voice and to use only a portion of the available items. At least two possibilities arise from the use of this method: (a) reduced reliability and (b) biased measurement through the use of only 'selected' items.

The former should require little comment, for it is highly unlikely that a human is able to utter a word in precisely the same manner two or more times at will. Therefore, the clinician employing monitored live voice is, in effect, presenting a different test to each patient. In all probability, some relatively wide variations in word production are tolerable and do not appreciably alter the measured threshold for speech, but it would seem preferable to take advantage of modern instrumentation which makes the rise of such variation unnecessary.

The latter possibility, though often recognized, receives impetus from the data brought out in this investigation. So long as there are differences in intelligibility among the stimulus words, regardless of their magnitude, there exists the chance of selecting predominantly easy or predominantly difficult words. Even in a 'descending level' presentation, it is possible that a relatively easy or difficult set of words will occur at a level very near the subject's threshold and cause his 'true' performance to be misrepresented. Further, the extent of such misrepresentation, and the prob-

TABLE I

Relative intelligibility of items on CID Auditory Test W-1. Items are ranked with respect to the mean sensation level at which first correct identification occurred.

| Item | SL in db |
|---|---|
| WORKSHOP | 2.7 |
| BASEBALL | 3.0 |
| HARDWARE | 3.5 |
| COWBOY | 4.3 |
| WOODWORK | 4.3 |
| PLAYGROUND | 4.5 |
| AIRPLANE | 4.7 |
| ICEBERG | 4.8 |
| RAILROAD | 4.8 |
| HOTDOG | 5.0 |
| NORTHWEST | 5.2 |
| SIDEWALK | 6.0 |
| SUNSET | 6.2 |
| BIRTHDAY | 6.3 |
| FAREWELL | 6.3 |
| STAIRWAY | 6.3 |
| EARDRUM | 6.9 |
| GREYHOUND | 7.0 |
| OATMEAL | 7.0 |
| WHITEWASH | 7.2 |
| ARMCHAIR | 7.5 |
| TOOTHBRUSH | 7.5 |
| MOUSETRAP | 7.7 |
| PANCAKE | 7.7 |
| HORSESHOE | 7.8 |
| DRAWBRIDGE | 8.2 |
| DAYBREAK | 8.3 |
| DOORMAT | 8.3 |
| DUCKPOND | 8.3 |
| HEADLIGHT | 8.3 |
| PADLOCK | 8.3 |
| SCHOOLBOY | 8.5 |
| INKWELL | 8.8 |
| MUSHROOM | 10.3 |
| GRANDSON | 12.2 |
| HOTHOUSE | 12.7 |

ability of its occurrence may be assumed to be proportional to the total range of intelligibility.

The obtained data must be considered only suggestive, due to the relatively small N. However, it is submitted that the precision of Auditory Test W-1 may be augmented by eliminating the extremes of the intelligibility distribution and recording the resultant shortened list for administration as a unit in a descending-level procedure.

In this regard, attention is directed again to Table I, particularly to bracketed set of 22 words which form part of the intelligibility distribution generated by the experimental subjects. The total range of this set is 3.5 db, and the number of words is small enough to lend itself to administration as a unit. The employment of these words in a randomized, recorded, descending level procedure would, on the basis of evidence presented here, offer a more efficient and precise measuring instrument than W-1 in its present form.

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# HEARING IN THE BAT, *MYOTIS LUCIFUGUS*, AS SHOWN BY THE COCHLEAR POTENTIALS

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The ability of many species of bats to find their way in darkness and to capture insects on the wing by the use of reflected sounds has commanded much attention in recent years, and the observations of Griffin (1) and others have brought a new understanding of this performance. Some of the problems remain unsolved, and one of these is the degree of precision with which the bat can direct its flight and detect minute objects when guided only by auditory cues. The situation seems to call for some unusual qualities of hearing, and especially for a high degree of sensitivity and discrimination in the upper frequencies.

This investigation is concerned with hearing in a common species of bat as revealed by measurements of the cochlear potentials. One previous study has employed this same method in the bat. Galambos (2) recorded these potentials in four species of insectivorous bats, *Myotis l. lucifugus*, *Myotis keenii septentrionalis*, *Pipistrellus subflavus*, and *Eptesicus f. fuscus*, and he was able to show that the range of their responses extends from the low frequencies – perhaps as low as 30 cps – to at least as high as 98,000 cps. He also obtained data on maximum responses under the conditions of his experiment.

## PROCEDURE

Our experiments were carried out with the little brown bat, *Myotis l. lucifugus* (Le Conte), specimens of which were collected while hibernating in an abandoned mine in northern New Jersey during February and March, and kept in a refrigerator at 10° C until needed. They were placed in groups of 10 to 12 in gallon–sized glass jars with perforated metal tops, and provided with drinking water and a piece of wire screening to cling to. The animals weighed from 3.5 to 7.0 grams, averaging 4.5 grams.

When used for cochlear potential measurements the animals were first revived and then anesthetized with Pernoston (sec–butyl bromallyl barbituric acid) in a dosage of 0.09 mg per gram of body weight, injected beneath

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the skin of the back. At this dosage the animals were suitably quiescent, though they could readily be stimulated to reflex activity, and usually continued in good physiological condition for several hours. A number of other anesthetics (Nembutal, Dial, Urethane) were used in preliminary tests, but gave much less satisfactory results.

Our procedure consisted of exposing the cochlea by a lateral approach and placing an electrode on the round window membrane, with another electrode in inactive tissue near by. The active electrode was either a platinum foil or a silver wire 0.002 inches in diameter whose tip had been held momentarily in a flame to produce a bead of about twice the wire diameter. These two electrodes gave the same results, but the wire was more easily manipulated in the restricted space of the bat's middle ear.

Sounds were produced by two loudspeakers, one of the dynamic type (Western Electric 555) for the low-frequency range (100 to 15,000 cps) and another of the condenser type with unstressed diaphragm for the high-frequency range (15,000 to 100,000 cps), connected to an audio oscillator through separate channels containing attenuators and amplifiers. A sound tube 28 inches long and 5/8 inches in inside diameter led directly from the condenser speaker through the wall of a shielded, soundproof room to the animal's ear, and another tube from the low-frequency speaker that joined this one at one side could be connected acoustically or shut off completely by manipulating a gate.

The animal was held in a mold of plasticene with the external ear sealed at the orifice of the sound tube. Ordinarily the auricle was left intact, and its opening was directed forward along the axis of the tube. For certain tests the auricle was removed and a cannula carrying an acoustic probe was interposed between the sound tube and the ear, as described later.

Measurements of sound pressure were made with a condenser microphone (Western Electric 640 A) that had been calibrated by the electrostatic actuator method over the range of 100 to 100,000 cps. The measurements were made by the substitution method, by sealing the microphone at the end of the sound tube at the same position ordinarily occupied by the animal's ear. The available sound pressure was 1000 dynes per sq cm or more in the low-frequency range and progressively smaller amounts down to 10 dynes per sq cm at 100,000 cps.

An electronic counter was used to hold the oscillator setting at every presentation within 3 cps of the proper value.

Two wave analyzers, one for the low-frequency range and another for

the high-frequency range, were used as selective voltmeters to measure the cochlear potentials.

## RESULTS

*Nature of the Cochlear Potentials.* The potentials obtained from the bat's cochlea in response to sounds resemble those recorded in many other animals. As shown in Fig. 1, the potential rises in linear fashion, or approximately so, as the sound pressure is increased, until at a high level the ear becomes overloaded and the curve passes through a maximum. The application of sound pressures beyond those required for a maximum will endanger the ear, and if sustained will produce irreparable damage. Care was taken in all these tests to stimulate the ear at the higher levels only long enough to obtain a reading, and this precaution was found to be especially necessary in the use of the very high tones.

The curves of Fig. 1 show maximum values of cochlear potentials of nearly 300 $\mu$V for 1000 cps, and less for the higher tones. This relation to frequency is systematic above 1000 cps as further results, given in Fig. 2, will demonstrate. As the frequency is raised the maximum values decline rapidly over a long course and then tail off beyond 60,000 cps, reaching something less than 1 $\mu$V at 100,000 cps.

*Sensitivity Functions.* Sensitivity measurements were carried out on 29 bats, mostly on the right ear, by presenting 32 or more tones over the range from 100 to 100,000 cps at the levels necessary to produce a standard response of 1 $\mu$V. Some of the results are presented in Figs. 3–6.

Fig. 3 shows the most common type of function. The sensitivity is poor for the low tones and increases rapidly as the frequency is raised to the region of 2000 cps and then more slowly until the region of 20,000 cps is reached. Here the curve falls precipitously to reach a sharp minimum—a peak of sensitivity—at 40,000 cps, after which it rises rapidly, with some irregularities, through the uppermost frequencies to 100,000 cps. In this ear the amount of the peak—its departure from the general course of the curve in the region of 40,000 cps—is of the order of 30 db.

The slight dip in the curve around 5000 cps was a regular feature, but the other small variations were of random occurrence from one animal to another. Repeated observations were usually in agreement within 5 db or less. Many of these variations we have found to be due to the activity of the middle ear muscles, and they were much reduced by increasing the depth of the anesthesia. It was not practical, however, because of the danger of respiratory failure, to maintain the animals at the deeper levels of anesthesia for the times required for extensive measurements.

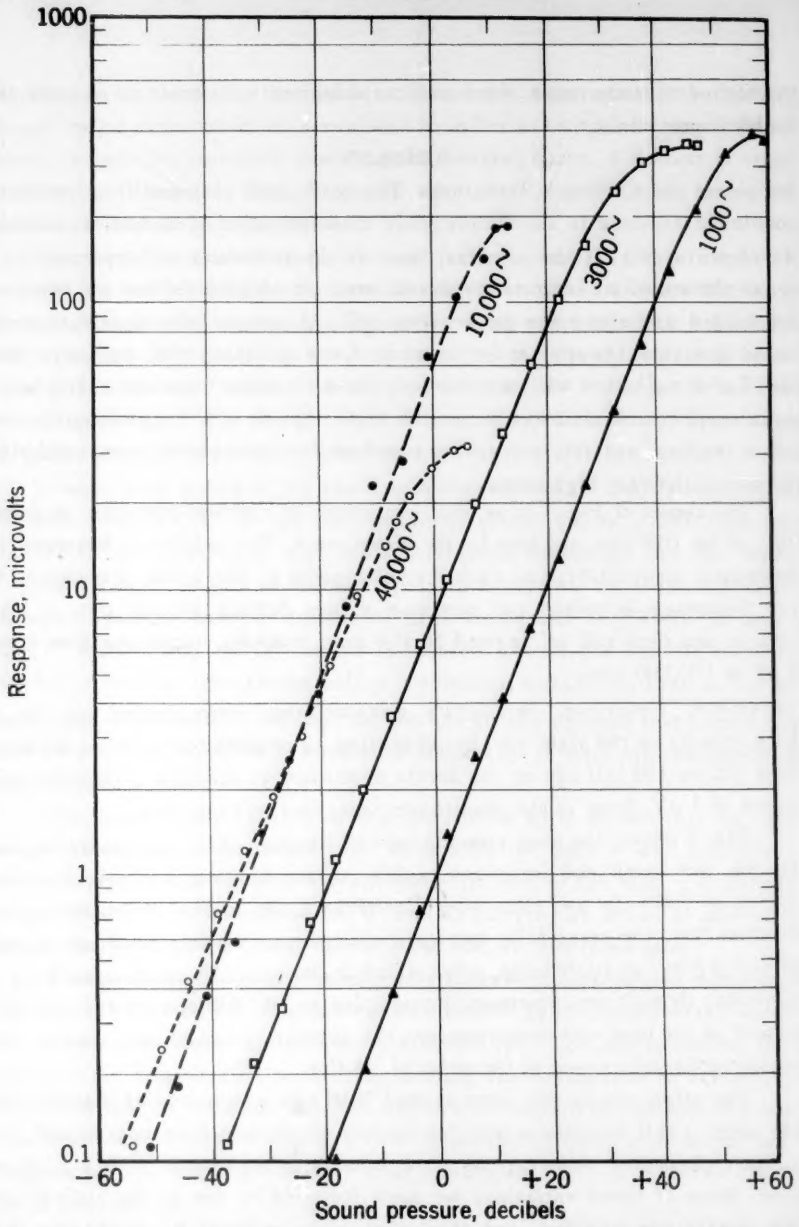


Fig. 1. Intensity functions for the cochlear potentials of the bat, Myotis lucifugus. Four curves are shown, and for each the response in microvolts is plotted for various amounts or sound pressure as expressed in decibels relative to 1 dyne per sq cm.

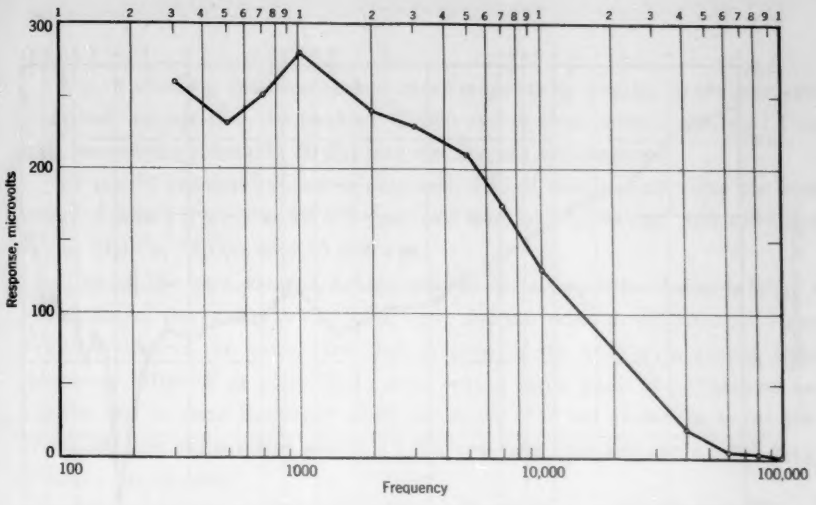


Fig. 2. Maximum values of cochlear potentials obtained for various stimulating tones.

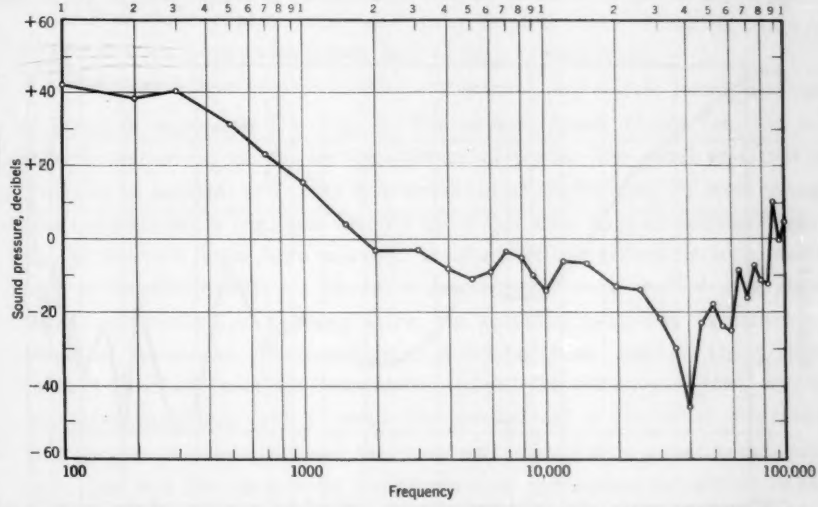


Fig. 3. Sensitivity curve for the bat's ear. Sound pressure is indicated in decibels relative to 1 dyne per sq cm. This curve is representative of the majority of bat ears. Note that sensitivity is portrayed in an inverse manner: the lower the curve the greater the sensitivity.

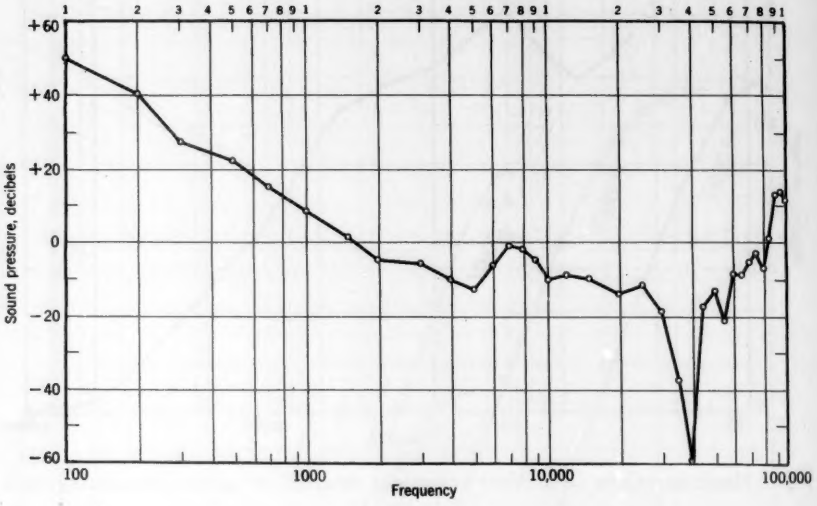


Fig. 4. Sensitivity curve for an ear with an unusually prominent peak at 40,000 cps.

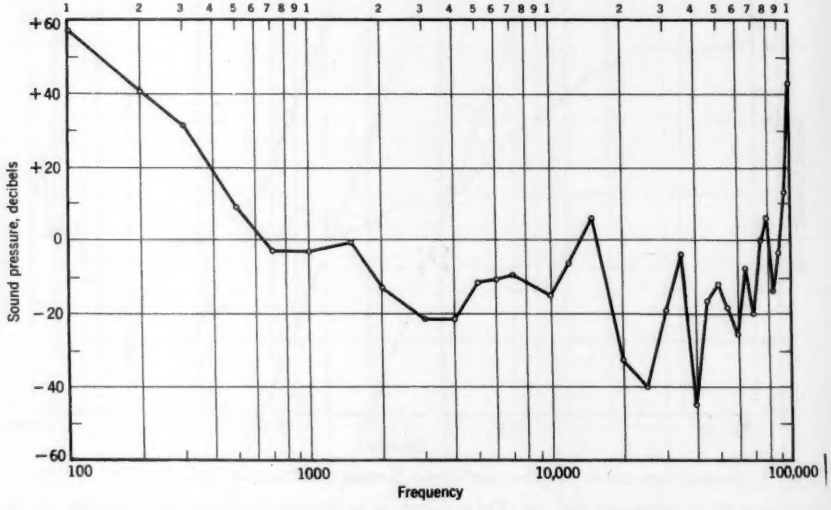


Fig. 5. A sensitivity curve containing two prominent peaks.

Fig. 4 shows a function that in most respects is similar to the one just described, except that the peak at 40,000 cps is even more prominent. This peak, amounting to nearly 50 db, was the largest encountered.

Of the 29 sensitivity curves obtained, 13 had single peaks like the foregoing, of which 8 were at 40,000 cps, two were at 15,000 cps, and one each was at 30,000, 35,000, and 55,000 cps.

Ten of the ears showed double peaks. An example is shown in Fig. 5, where one of the peaks is at 25,000 cps, and the other at 40,000 cps. These peaks are about the same size, but in most of the ears with double peaks they were different in size. Often there was a major peak at 40,000 cps and a minor one at some frequency above or below. One ear showed a major peak at 60,000 cps and a minor one at 12,000 cps, and this was the widest range of peaks encountered.

Two of the ears exhibited triple peaks. One of these had a major peak at 50,000 cps and minor ones at 10,000 cps and 25,000 cps, and the other had a major peak at 60,000 cps and minor ones at 15,000 and 40,000 cps.

All of these peaks, single and multiple alike, fell within the range of 10,000 to 60,000 cps, with nearly half of them at 40,000 cps.

There were four ears in which no prominent peaks were found, and one of these is represented in Fig. 6. The general shape of the function resembles the others except for the absence of peaks. The usual variation at 5000 cps is present, and there is a small jag at 40,000 cps. We must recognize the possibility that here as well as in the other ears an extremely narrow peak could have been missed, as observations ordinarily were made only at discrete points as shown. A few animals were studied at a great number of closely spaced frequencies, but no additional peaks were found.

*Origin of the Peaks.* The presence of prominent peaks such as those found in most of these functions immediately raises the question of their origin, and these variations look so much like mechanical or electrical resonances that they arouse the suspicion that they may represent an experimental artifact. The fact that there were variations from one animal to another in the number and location of the peaks detracts from the belief in an instrumental cause, but nonetheless we have gone to considerable lengths to investigate the possibilities.

The condenser microphone was given early attention because it was known to have an internal resonance in the region of 40,000 cps, caused by the air cavity behind its backplate. A new calibration of this instrument was carried out, and it agreed in all respects with the earlier one. All other pieces of apparatus, includ -

ing the amplifiers and wave analyzers, were carefully checked and found to be operating correctly. Thus, we were unable to discover any peculiarity of the electrical equipment that would account for the peaks.

To test the possibility of resonance in the sound tube leading to the ear, this tube was manipulated in several ways designed to alter its characteristics. It was varied in length, strands of wool were inserted in it, and it was filled with smaller thin-walled tubes of 1/8 inch bore. This tube was also terminated in a length of 1/8 inch tubing that made the junction with the ear. These manipulations changed the tube characteristics in varying amounts, but when these characteristics were taken into account by the calibration procedure, the sensitivity functions took the same forms as before. The peaks remained in the same locations and maintained the same amplitudes.

All the measurements thus far involved a substitution of the condenser microphone for the ear at the orifice of the sound tube, and this substitution assumes that the reflection characteristics of these two when sealed at the orifice are not significantly different. To test the possibility that this is not a proper assumption a special probe was developed with sufficient sensitivity to cover the range of frequencies up to 85,000 cps. This probe consisted of three tubes of different lengths (1 9/16, 2, and 3 inches) leading from the end of a sound cannula to the insert piece that was held by a cap over the condenser microphone diaphragm, and it was calibrated to give indications of the sound pressures existing at the end of the cannula. This cannula and probe combination was used in two ways. In some animals the auricle was removed and the end of the cannula was sealed over the external auditory meatus. Its contained probe tubes were then within 2 mm of the drum membrane, and thus gave measures of the stimulation at that place. In other animals the auricle was left intact and the cannula was placed at its entrance. In both situations the same forms of sensitivity functions were obtained as before. From all these observations we concluded that the peaks usually observed are truly characteristic of the bat's ear.

Our further problem was to determine the particular part of the ear that is responsible for the peaks. We considered several possibilities for their production through resonance in the external or middle ear, (a) by a cavity resonance of the auricle, (b) by resonance in the opened bulla, acting as a chamber resonator, (c) by mechanical resonance of the ossicular chain or some of its parts, and (d) by membrane resonance of the eardrum. These possibilities were tested by the following series of experiments.

(1) It has already been mentioned that in some of the animals the auricle was removed and the sound cannula applied directly to the auditory meatus. The usual form of sensitivity functions, with prominent peaks, were obtained with this procedure.

(2) In one animal the sensitivity was first measured in the usual way, with the bulla open, and then this opening was sealed with wax, restoring the bulla to its normal condition. The results are represented in Fig. 7 as differences in decibels

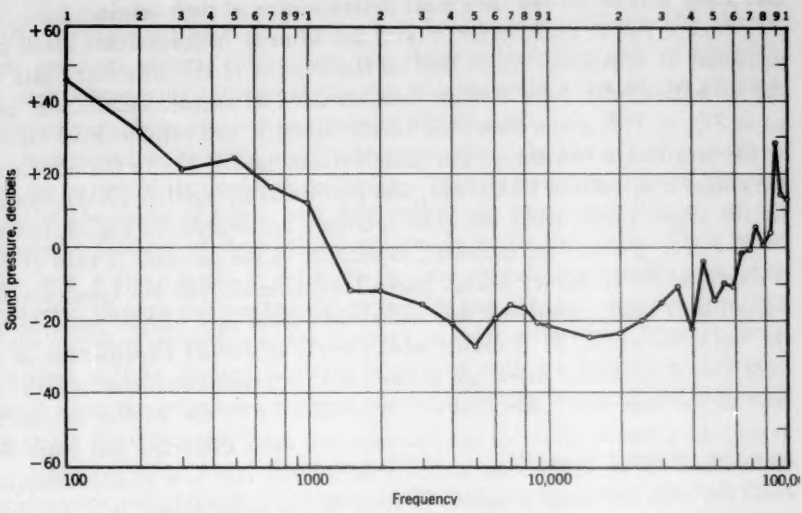


Fig. 6. A sensitivity curve without any large peaks.

between the two conditions, with negative values signifying greater sensitivity for the open bulla. As may be seen, there are some differences, but they are generally small and mostly in favor of the open bulla condition. These variations were not such as to alter the general form of the sensitivity function, which continued to exhibit a major peak at 60,000 cps and a minor one at 12,000 cps.

(3) In another animal the sensitivity function was obtained as represented by the solid line of Fig. 8, and showed a major peak at 50,000 and a minor one at 20,000 cps. The ossicular chain was then broken and the observations repeated, with results as shown by the long-dashed curve of this figure. There was great loss of sensitivity, amounting at some points to 50 or 60 db, and averaging 41 db for tones up to 15,000 cps and 31 db for the higher tones. The two peaks remained, with only minor changes. Finally, a tear was made in the drum membrane and the measurements were carried out once more, with results as shown in the short-dashed curve. As may be seen, these further changes were moderate in amount, and varied over the frequency scale. The two peaks remained.

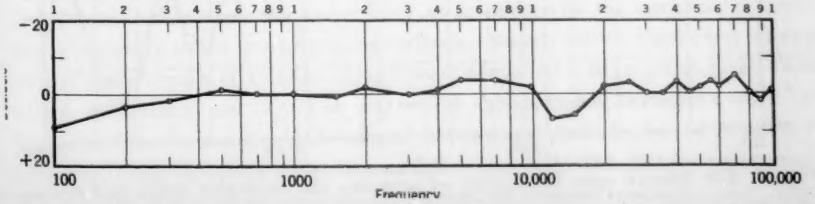


Fig. 7. The effects of open and closed bulla on sensitivity. Negative values signify that the sensitivity was greater when the bulla was open.

The above tests seem to exclude the auricle and the middle ear as sites for the production of the peaks of sensitivity seen in most of the ears. Further study will be needed for a final determination of their origin.

*The Middle Ear Characteristic.* Fig. 8 has already indicated that grave impairments of sensitivity result from an interruption of the ossicular chain at the incudostapedial joint. Further data, obtained on another animal, are given in Fig. 9. This graph shows the losses directly, and exhibits more clearly the relation to frequency. The most serious losses are in the middle of the range, from 1000 to 10,000 cps, and progressively smaller losses appear for the higher tones. Much the same relations are evident in Fig. 8, though the two sets of data vary in detail, especially in the amounts of loss at the two ends of the frequency scale. These losses result from the simultaneous operation of three conditions that enter when there is a simple breaking of the ossicular chain, as revealed more clearly in earlier experiments of a more extensive kind carried out in the cat (3). These conditions are (a) a loss of the impedance matching normally afforded by the middle ear mechanism, (b) a barrier effect of the disconnected drum membrane and outer ossicles, and (c) an interaction between the sounds that now simultaneously enter the oval and round windows on more nearly equal terms. It is not possible at this time to assign the proper portions of the loss here seen to these three conditions, and such an assignment must await the carrying out of further manipulations like those done in the cat.

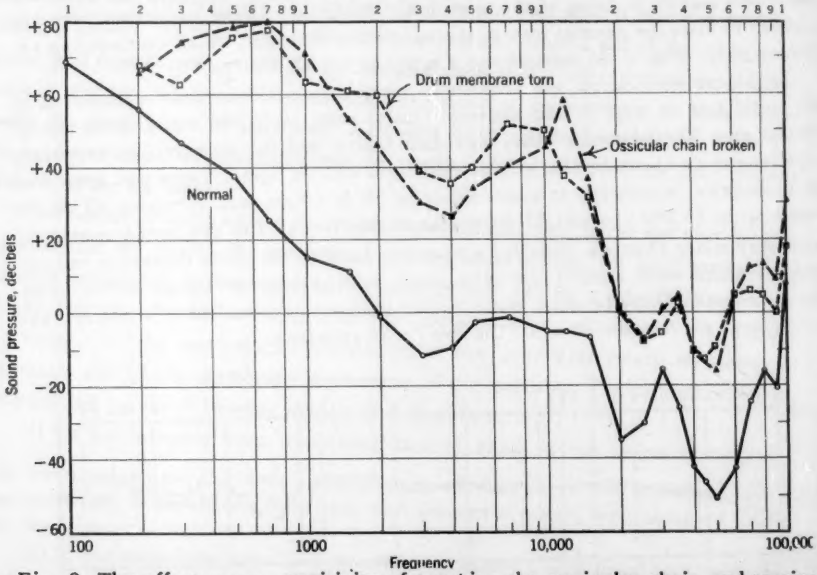


Fig. 8. The effects upon sensitivity of breaking the ossicular chain and tearing the drum membrane.

## DISCUSSION

No thoroughgoing behavioral studies have been made of hearing in bats, though there are many general indications that these animals are able to perceive the high frequencies. Dijkgraaf (4) was able to train a bat of the species *Nyctalus noctula* to respond to a tone of 40,000 cps.

It is possible to make some inferences about the hearing of an animal from the nature of its cochlear potentials. These potentials arise in the hair cells of the organ of Corti, and they reflect the characteristics of all the peripheral portions of the auditory system up to the hair cells. Their presence over a given range is evidence that the stimulating sounds have been conducted through the mechanical system of the ear, and that the dendrites of the cochlear nerve fibers are exposed to their influences. Whether these dendrites will be excited, and the degree of their excitation, will depend simply upon the magnitude of these potentials at the bases of the hair cells where the dendrites ramify.

Our knowledge about these magnitudes is ordinarily indirect, because an electrode only records a fraction of the true potential that the hair cells generate. When an electrode is on the round window, as it has been in most of the systematic measurements, it records the summed potentials of many hair cells throughout the cochlea, but because of its location at the basal end of the cochlea it records these potentials in a biased manner. Those at the basal end are favored over the ones farther away (5).

We can obtain an idea of the relation between the cochlear potentials and hearing in the general sense by comparing these two in the same animals, and sufficient data are available for this comparison in five species of laboratory animals: marmosets, rhesus monkeys, cats, guinea pigs, and pigeons (6). In these there have been determinations of threshold acuity by behavioral methods and measurements of cochlear potentials over a broad range. The data are especially complete in the cat, where these two kinds of measurements have been carried out in the same ears(7).

A comparison of these two functions shows that there is a close correspondence between them at the low-frequency end of the range, and then as the frequency is raised the acuity shows a significantly greater rate of improvement than does the sensitivity as measured by the cochlear potentials. Evidently there are neural operations through which the effectiveness of the higher tones is enhanced, and some hints have been offered as to what these operations are (8). The degree of enhancement increases with the frequency over a considerable range. Beyond a certain region of frequency, however, these enhancing operations falter and fail. The turning point seems to be in the region of 10,000 cps for marmosets, rhesus monkeys, and cats,

and is lower, perhaps around 4000 cps, for guinea pigs and pigeons. Thereafter the acuity declines precipitously, while the cochlear potential function continues on a uniform level for a span, and then in higher frequencies shows a fairly rapid fall. The upper limit of hearing is therefore reached at a frequency at which the cochlear potentials are still readily discernible. In marmosets an upper limit is found between 25,000 and 35,000 cps, and in cats this limit is at 60,000 or 65,000 cps. In both these species the cochlear potentials may be recorded all the way to 100,000 cps, but their magnitudes in this upper range are about 10 times greater in cats than in marmosets for the same stimuli.

These principles may now be applied to the cochlear potential data to give an indication of the acuity of the ear of the little brown bat. Over the entire lower end of the frequency range, from 100 cps at least as far as 20,000 cps – unless there are peaks that fall in the upper end of this regi – on – the cochlear potential sensitivity of bats is much inferior to that of all the mammals mentioned above, and is inferior to that of pigeons also up to 1000 cps. It would seem that bats hear the intermediate range of tones only poorly, and the extreme low tones probably not at all.

Only as the uppermost region of frequency is reached do the bats begin to compare favorably with the other animals for which high–frequency data are available. Yet even here they are inferior in the regions where peaks fail to appear. In the absence of peaks, they are about 40 db worse than cats and 20 db worse than marmosets at 20,000 cps. At 30,000 cps these differences are still 25 db in favor of cats and 5 db in favor of marmosets, and they continue in about this relation all the way to 100,000 cps.

It is only when peaks appear that the bat attains a degree of sensitivity that equals, and usually exceeds, that of these other mammals. At 40,000 cps the bat ear shown in Fig. 3 is 5 db more sensitive than one of the better cat ears, and the ear shown in Fig. 4 is 20 db better at this frequency. Indeed, these ears, and nearly all of the other ears studied, when evaluated in terms of the sound pressure required to produce a standard potential, are superior within the compass of their peaks to all other ears so far studied at the same frequencies. When the comparison is made between the point of the peak and the most sensitive point anywhere in the range of the other animals, the bat still fares well, and the exceptional one shown in Fig. 4 remains superior.

How far the bat's upper limit of hearing extends remains a question. From the data at hand it does not seem that he is in any respect superior to the other mammals, the marmoset and the cat, for which high–frequency data are available. No peaks were found beyond 60,000 cps, and thus it be-

comes doubtful that the bat hears sounds above this point unless they are of extraordinary magnitudes.

It appears that the bat, limited by a general poverty of sensitivity, is compensated somewhat in the appearance of one or more peaks in his upper frequency range. This characteristic serves the animal well because the peaks occur in the region most useful to him in echolocation. The voice of *Myotis lucifugus* during echolocation, according to Griffin, consists of pulses beginning at a high frequency of perhaps 72,000 cps and falling during their brief course to 33,000 cps at the end. The usual range of the voice recordings was from 30,000 to 80,000 cps, with most of the energy of the pulse around 50,000 cps. Some of the records included frequencies as high as 115,000 or even 153,000 cps, but it is probable that these were overtones. It is evident that the sweep of frequency of about an octave in the orientation cry will include the sensitivity peak of the animal's ear, and thus this portion of the cry when reflected by an object will be heard. Also the hearing of the direct cry will be modified, with the frequencies outside the peak greatly reduced in relation to the peak frequencies. This reduction may be a considerable advantage, especially when the object is near, as it effectively narrows the temporal span of the pulse, and the echo will be less likely to be overlapped and obscured by the part of the cry that is still going on.

It would seem most appropriate for the bat's orientation cry to be conformed to the peak sensitivity of his ear, and not only to include the frequencies within the peak but to have the greatest energy there. To what extent this may be true is doubtless a matter of the control of voice production. It may well be that the emission of exact high frequencies is as difficult for the bat as it is for opera singers, and his recourse is to traverse the region. The singer does something like this in the use of the vibrato. By sending forth an octave of frequencies the bat is better insured of obtaining an audible echo.

A matter of special interest is the ability of bats to engage in echolocation in the presence of extraneous noise of many kinds. They are often observed flying in caves in complete darkness, all sending forth their pulses and successfully avoiding the cave walls and one another. Why is not this general clamor a source of serious disturbance to the flying bats?

Griffin has reported several experiments carried out by him and his associates to investigate this problem. Early tests with single tones of moderate intensity from crystal and magnetostrictive sources produced no interference with the bat's performance. The same was true of a number of later experiments in which noises were used and the bats were confronted with arrays of wires that provided a severe test of their navigating skill.

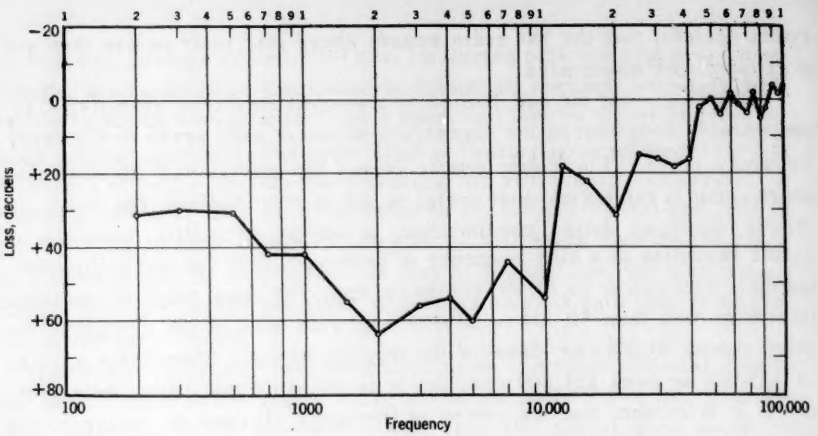


Fig. 9. The effects of breaking the ossicular chain, represented as decibels of loss from the normal condition.

Only when particularly powerful sources were employed were the bats affected. When a siren was sounded at almost a dangerous energy level the bats were disturbed and refused to fly. They reacted similarly when subjected to thermal noises representing a broad spectrum of frequencies and including their orientation sounds, when these noises were made sufficiently intense. At surprisingly high levels of this noise, however, they performed well when forced to fly, even though exhibiting an obvious reluctance to do so. When the wire avoidance tests were carried out with *Plecotus raffinesquii*, a large-eared bat that uses rather faint pulses in its ranging, it was possible to show a deterioration of performance when the wires were particularly fine and the thermal noise was presented at levels of 60 to 80 db above 0.0002 dynes per sq cm (i.e., at 0.5 to 2 dynes per sq cm).

Griffin discussed various possibilities that may be brought forward in explanation of these results. The following four were given particular attention.

(1) The bat's hearing may be sharply tuned, so that the animal is able to listen to the echoes and ignore the noise. In human hearing it is known that the hearing of a given tone is impaired not by the whole of a broad band of noise, but only by that part in the immediate region of the tone, a part that has been termed a critical band. For example, a tone of 9000 cps presented to a human ear will be masked by noise components whose frequencies fall between 8690 and 9310 cps; the critical band for this frequency is 620 cps wide. The human data do not extend to higher frequencies, but the critical bands widen rapidly as the frequency rises. And yet Griffin's calculations of the selectivity that would be necessary to explain the performance of *Plecotus* under the conditions of his experiment indicated a bandwidth of only 6 cps. This figure is so far away from expectations based on human hearing that Griffin was inclined to doubt this explanation and to turn to others.

(2) A second possibility is that because of his large auricles the bat's hearing may be sufficiently directional in its characteristics that by turning the head or the individual auricles at suitable angles he is able to maximize the echo and reduce the disturbing noise. Attempts were made by Griffin in some of the wire avoidance tests to counter such a maneuver by presenting the noise along the line of flight or else to distribute it so generally over the field that it could hardly be avoided, and yet for the larger sizes of wires, those over 0.5 mm in diameter, the avoidance scores were not significantly affected.

(3) Mention was made of a third possibility, that the bats in their orientation employ harmonics of their cries and not the fundamental frequencies, and thereby extend their listening to a region well beyond the noise bands that were being presented. This explanation would of course fail when the cries of other bats became the disturbing sounds.

(4) A final suggestion, which to Griffin appeared the most likely, is that it is the sweep of the frequency that the bat perceives. Such a sweep is more distinctive than any character of the noise.

These possibilities of course are not mutually exclusive, and any combination of them might explain the bat's performance. We are now in a position to reevaluate them in the light of the present experiment.

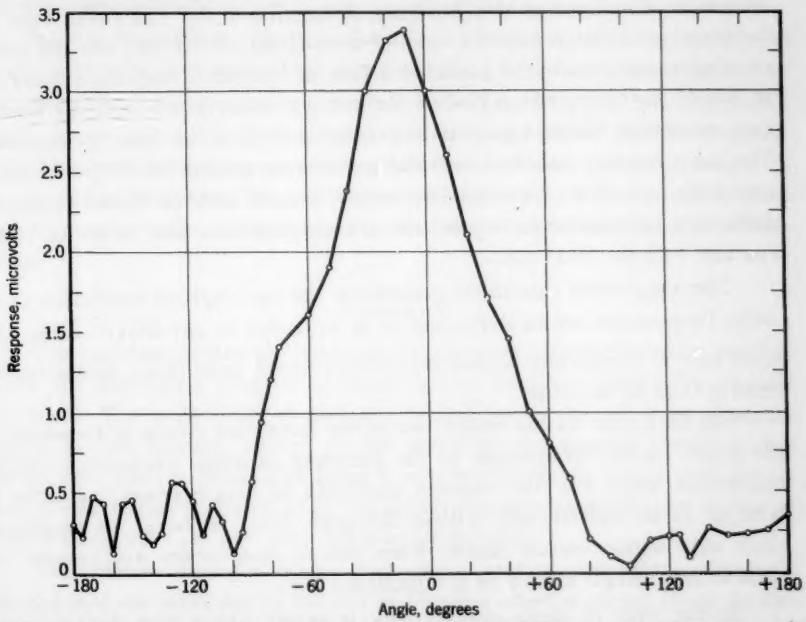


Fig. 10. The directionality of the bat's ear for a 40,000 cps tone. The zero angle represents a position in which the animal was facing the sound source, with the sagittal axis of the head in line with the tube. Positive degrees represent a clockwise rotation of the head, and negative degrees a counterclockwise rotation. At ± 180° the sound was directly behind.

Our results definitely favor the first explanation, that the bat's ear is sharply tuned so that the echo is selectively received, Many of the peaks at 40,000 cps showed slopes of 80 db per octave, and some were even steeper. Sounds whose energy falls elsewhere in the frequency scale will be discriminated against by 20 to 30 db in most ears and by as much as 40 db in many of them.

The explanation in terms of directionality also receives support from our experiments. We made measurements of the cochlear potentials in one ear with the bat in an open field, with a steady tone coming from a tube 5 inches away, and then rotated the body about the vertical axis of the head so that the auricle took various angular positions. The results of one of these experiments are shown in Fig. 10. Here the stimulating tone was 40,000 cps, zero degrees is the position facing the source, positive angles represent a turning clockwise, and negative angles represent a turning counterclockwise. The most favored angle was $-10°$, because the measurements were made on the right ear and its auricle was turned more directly toward the source at this position. A rotation of 60° clockwise from the maximum position produced a loss of sensitivity of 7.1 db, and the same rotation counterclockwise produced a loss of 5.8 deb. Rotations beyond 100° in either direction, which placed the animal facing away from the source, gave somewhat variable potentials averaging 23 db down from the maximum. The bat's hearing therefore exhibits a moderate amount of directionality to this high tone. The directionality was of course less for lower tones; the difference between the facing and the averted positions was 10 db for 10,000 cps and 7 db for 5000 cps.

The suggestion that in its orientation the bat employs harmonics of the pulse frequencies seems definitely to be excluded by our observations. The rapid loss of sensitivity beyond 60,000 cps would make these harmonics extremely faint or inaudible.

The idea that the bat makes use of the downward sweep of frequency in the pulse for its recognition in the presence of noise encounters certain limitations also. For the common condition of single peaks, an echo so faint as to be audible only within the peak could be heard as varying in pitch only within narrow limits. When two or more peaks are present the pitch interval might indeed be a significant cue.

In the light of these observations it seems likely that the bat makes use of two or three measures in his discrimination of the echo from other sounds.

The first step in his selection of the echo over disturbing noises is provided by the directional characteristics of the auricle, and his movements of

auricle and head give him a degree of control in the situation. He can direct the pulse to some extent and then can listen for it with the ears pointing in a chosen direction, and in this way can gain systematic information about an obstacle in his path. The noises that he hears will have no such systematic and controllable features.

The differentiation of the echo will be further aided by the selectivity of the bat's ear. When peaks of sensitivity occur, as they do in the great majority of ears, the echo will be favored by large amounts – usually 30 db or more – over sounds of frequencies outside the peaks. However, this characteristic will not serve in discriminating against sounds, such as the cries of other bats, whose frequencies fall in the peaks.

Finally, as already suggested, those bats whose ears contain two peaks may perceive two successive sounds of different pitch as the echo sweeps through its frequency range, and these, representing an interval of pitch and a temporal relation determined by the vocalization itself, will provide a distinctive cue.

On this formulation, the occasional bat whose ear lacks any prominent peaks will be at a disadvantage in orientation. It seems reasonable to expect individual differences in this ability. Griffin spoke of 'bumbling bats,' those whose orientation performances fall far short of the skillful majority. This blundering of certain ones has often been attributed to sleepiness, ill health, or carelessness, but it is entirely possible that it has a more serious and permanent basis, in inadequacies of auditory sensitivity and discrimination.

## SUMMARY

The cochlear potentials produced by acoustic stimulation were used to study the peripheral sensitivity of the ear of the little brown bat, *Myotis lucifugus*. The sensitivity of this ear is inferior to that of other mammals tested in this manner, except in the very high frequencies, those above 20,000 cps, and for these high tones it reaches favorable levels only in certain narrow regions. These peaks of sensitivity appear within the region of 10,000 to 60,000 cps, and most often at 40,000 cps.

Some inferences are drawn from these results concerning the bat's hearing and the relations to the act of locating objects during flight by listening to the echoes of its own cries.

Results are given also on the maximum potentials of the bat's ear and the effects of an interruption of the ossicular chain.

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# THE EFFECT OF BINAURAL BEATS ON PERFORMANCE *

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This study originated with an interest in the effects of post–stimulation tinnitus on performance. However, initial investigation indicated that it was experimentally impractical to produce a tinnitus of sufficient duration in the laboratory to test its behavioral effects(4). For this reason, another type of auditory phenomenon was sought that would share some of the characteristics of post–stimulation tinnitus, but could be more readily manipulated in the laboratory. Final interest focussed on binaural beat stimulation (12) as a reasonable alternative to post–stimulation tinnitus since subjective beats are involved in both cases and, presumably, both phenomena are of central origin. This presumption of central origin for post–stimulation tinnitus follows from the observation that beating tinnitus preserves the essential characteristics of the inducing stimulus.

The phenomenon of binaural beats is best described as a periodic fluctuation in loudness that occurs when two tones of slightly different frequency are led separately to the two ears. Since these subjectively experienced fluctuations in loudness correspond in rate to the difference in frequency of the stimulating tones, the assumption is that the afferent flow in each auditory nerve must vary at the corresponding stimulus frequency (8). Thus the resulting phenomenon, involving binaural interaction, is apparently related to the interaction of two differing afferent inputs in some common neural center or pathway. With an auditory effect induced in this manner, the organism is subjected to a stimulus which cannot be ignored or 'tuned out', and it is not unreasonable to hypothesize an effect upon performance.

As pointed out in the review by Berrien (2) and demonstrated in later studies by Barrett, (1), Egan (3), and Smith (11), noise has been found to have no significant effect upon various performance and personality vari-

* This study was undertaken in partial fulfillment of the requirements for a Doctor of Philosophy degree under the supervision of Drs. Merle Lawrence and Donald G. Marquis, of the University of Michigan, and was supported in part by the Research and Development Division, Office of the Surgeon General, Department of the Army, under contract DA–49–007–MD–634. All work was carried out in the Physiological Acoustics Laboratory, Institute of Industrial Health, directed by Dr. Lawrence.

ables. However, it seems advisable to distinguish between auditory stimuli which originate purely in the peripheral end–organ – as in the case of ordinary noise – from binaural beats which must involve some interaction process in the central nervous system. It is quite possible that the neural process underlying binaural beats could produce performance decrement, while a more conventional auditory stimulus does not. The hypothesis is that binaural interaction induced by binaural beat stimulation would produce significant performance decrement, while comparable auditory stimulation not involving binaural interaction would have no such effect.

## GENERAL PROCEDURE

This study is divided into two separate experiments which are described in detail below and presented schematically in Fig. 1. The general procedure was to place the experimental subject in a soundproof room with silent earphones in place(to control for the effects of equipment) and obtain an initial score on the performance tests. On two subsequent sessions the same measures were obtained while the subject was being stimulated through the earphones with an appropriate auditory stimulus. The control group was required to take the performance tests three times in order to determine the effect of practice on test score.

The signals were generated by two audio frequency oscillators with attenuation networks, which were then led into an audio–mixer with a switching arrangement that would allow easy and accurate selection of the desired stimulus condition. The attenuation networks provided an easy means for threshold determination and the mixer made possible an externally beating stimulus required for one part of the study. A cathode–ray oscilloscope permitted visual monitoring of the audio signals.

*Subjects.* A total of 40 subjects for the various experiments in the study was recruited from the Air Force R.O.T.C. Detachment of the University of Michigan. Adequate motivation was facilitated by the fact that these subjects were Air Force men participating in a project of interest to the Air Force. For purposes of standardization, all instructions and orientation material was prepared beforehand and read to each subject. The subjects were told that the study was aimed at determining the effects of various sounds upon human beings as they performed a simple test. All subjects were considered to have at least normal hearing due to the fact that they had passed the cadet selection physical. However, auditory thresholds were determined on the first sixteen individuals in order to arrive at a stimulus intensity closely approximating 60 db above their average threshold. These first sixteen subjects were assigned to an initial exploratory study; another

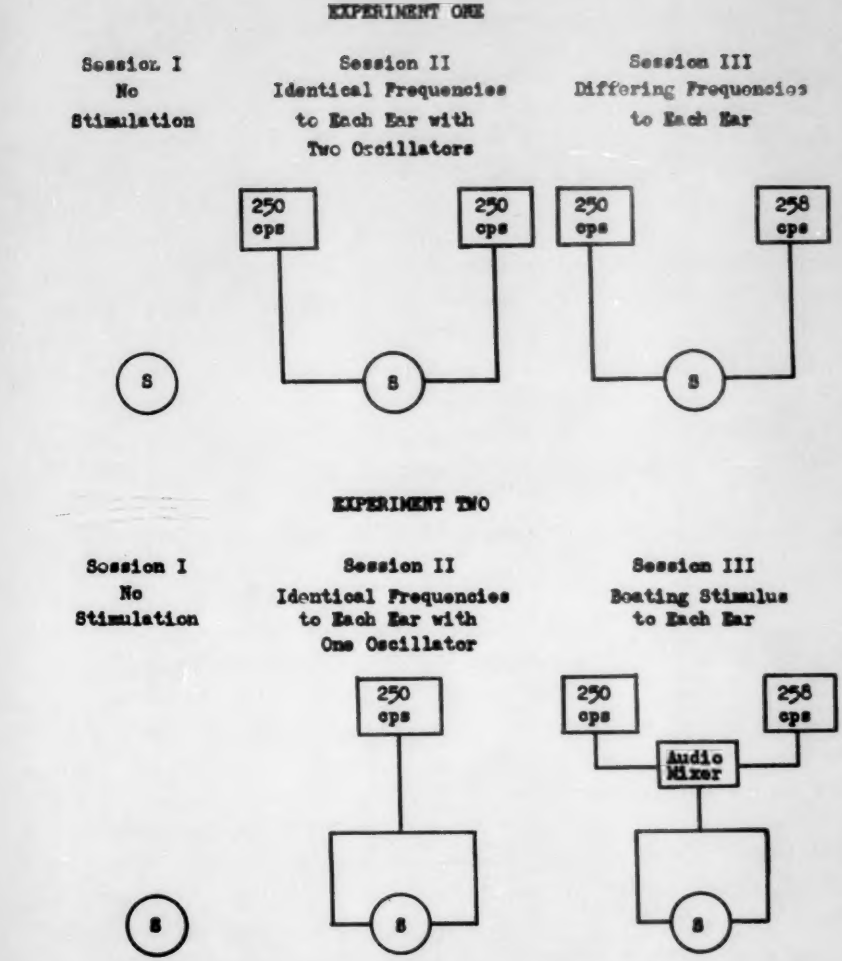


**Figure 1. Schematic representation of auditory stimuli presented to experimental subjects in Experiment One and Experiment Two.**

sixteen subjects were used in Experiment One, and eight subjects were used in Experiment Two.

*Performance Tests.* One test of performance used in the exploratory study as well as in Experiments One and Two reported here was the *MacQuarrie Test for Mechanical Ability,* published by the California Test Bureau. This instrument was selected because of its relative simplicity of administration and scoring, and the fact that it appears to involve little previous learning or experience. In addition to a total score, there are seven subtest scores which offer the possibility of an item analysis. This test is reported to be relatively free of practice effects. This proved to be untrue for the experimental population in this study, but still may be less than with other instruments. In Experiment One, in addition to the MacQuarrie test, three subtests from the *Thurstone Primary Mental Abilities Tests (PMA)* were used, namely, Number Ability, Space Ability, and Memory Ability.

## EXPERIMENT ONE

*Procedure.* Experiment One involved sixteen subjects – eight experimental and eight control – matched on the basis of initial MacQuarrie test scores. There were three experimental sessions as follows: *Session I* in this experiment, and in Experiment Two below, provided a baseline score on the performance measure without auditory stimulation. In *Session II* the experimental subjects repeated the performance test while a pure tone of 250 cps was presented through the two earphones. The tone for each ear was generated in a separate oscillator. These two oscillators were kept in phase by manual control through the visual monitoring of a simple Lissajous figure. (As indicated in the later discussion, this manual control did not keep the tones to the two ears in *exact* phase with one another). During *Session III* the experimental subjects took the performance test for the third and final time. In this final session, there was a frequency difference of eight cps between the tones presented to the two ears. That is, one ear was presented with a 250 cycle tone and the other ear with a 258 cycle tone. This kind of stimulation results in the production of a subjectively beating sound, with a periodic fluctuation of eight per second. As previously mentioned, the control subjects also took the performance test three times, but all sessions were conducted in the same manner as *Session I.* A 250 cps tone was used in this experiment, since an exploratory study had indicated that subjective beats were pronounced at this frequency.

*Results.* The results of this study are presented in Table 1. Note that the MacQuarrie test scores (MAC) of the experimental and control groups in *Session I* were quite closely matched. Also included in the table are the scores on the Number Ability (N), Space Ability (S), and Memory Ability (M) subtests of the Thurstone PMA test.

TABLE 1

RAW SCORE MEANS FOR EACH TEST IN SESSIONS I, II, AND III

| Session | MAC | N | S | M |
|---|---|---|---|---|
| | | Experimental Group | | |
| I | 78.75 | 88.87 | 69.75 | 12.75 |
| II | 75.13 | 96.25 | 73.88 | 15.75 |
| III | 74.38 | 94.88 | 80.38 | 17.00 |
| | | Control Group | | |
| I | 77.75 | 90.88 | 72.50 | 12.50 |
| II | 85.63 | 96.63 | 83.13 | 17.38 |
| III | 97.25 | 108.75 | 93.63 | 17.75 |

Examination of Table 1 shows that the effect of auditory stimulation in *Sessions II* and *III* does produce a lowering of the MacQuarrie test scores. Further, the stimulation tends to lessen the improvement in scores on the PMA subtests when such scores are compared with those of the control group. In order to check the matching of these two groups, F and t–tests on differences in initial scores were computed for the MacQuarrie test with no significant differences indicated. To ascertain the significance of differences in scores obtained across sessions, t–tests were obtained. These results are reported in Table 2.

TABLE 2

t–TESTS OF TEST SCORE DIFFERENCES BETWEEN EXPERIMENTAL AND CONTROL GROUPS IN SESSIONS I, II, AND III

| Test | Sessions | | |
|---|---|---|---|
| | I–II | II–III | I–III |
| MAC | Sig. beyond .01 | Sig. beyond .02 | Sig. beyond .01 |
| N | NS | Sig. at .01 | Sig. at .10 |
| S | NS | NS | NS |
| M | NS | NS | NS |

Table 2 indicates that the obtained differences on the MacQuarrie test are highly significant. The subtests of the PMA battery do not demonstrate statistically uniform differences in performance, even though the raw score means tend to fall in the predicted direction. It is necessary to conclude, on the basis of the present data, that Number Ability, Space Ability, and Memory Ability, as measured by the Thurstone PMA Tests are not significantly influenced by the auditory stimuli (9).

The results seem to leave no doubt, however, as to the negative effect of the auditory stimulation upon mechanical performance ability as measured by the MacQuarrie Test. This test is composed of seven subtests, each contributing to the total score: Tracing, Tapping, Dotting, Copying, Location, Blocks, and Pursuit. For purposes of analysis, the score differences on each of these subtests from *Session I* to *Session III* was determined and t-tests computed to determine significant differences. It was found that only the Tracing, Tapping, and Dotting subtests reveal any significant difference scores (9). However, it should be noted that the subtests were given in only one order and the subtests affected were the first three. This raises the question whether the effect is related purely to the subtests or if it is an effect of order of presentation.

The subtests were further analyzed in terms of number of items completed and number of errors committed. The results indicate that the number of errors per subtest is not a significant factor in the differential scores between control and experimental subjects, but that the number of items completed is (9). The most that can be concluded from this exploratory analysis of the subtests is that the auditory stimuli seem to act in some way to hinder or retard manual coordination of the simple type required on the MacQuarrie test.

## EXPERIMENT TWO

This experiment was necessitated by the nature of the results obtained in Experiment One. The first consideration was to examine the fact that performance decrement resulted in *Session II* of Experiment One even though there were no subjective beats reported. However, a review of the procedure of this session revealed that the method of manually balancing the two frequency oscillators permitted a phase shift averaging two to five per minute. Thus it was necessary to control for this in the design of the present experiment. The second consideration was an attempt to rule out the purely annoying and distracting effects of the beat stimulation as the cause of the performance decrement in *Session III* above. If the distraction itself

was responsible for the performance effect, the neural mechanism underlying the binaural beats might not have been involved at all.

The possible influence of the slow phase shift in *Session II* of the first experiment was evaluated by presenting a tone binaurally, but having the tone originate from a single oscillator. The distracting effect of the binaural beats was assessed by presenting an actually beating tone to both ears.

*Procedure.* Eight experimental subjects were matched on the basis of initial MacQuarrie test scores with the control subjects of Experiment One, thus eliminating the need for another separate control group. *Session I,* as in Experiment One, was the initial baseline performance measurement without stimulation. In *Session II* the experimental subjects repeated the performance test while being presented with a pure tone of 250 cps, generated by a single oscillator and led to both ears through a dividing network. During *Session III* the subject took the performance test while being stimulated in both ears by a beating tone. This stimulus was produced by leading the 250 cycle output from one oscillator and the 258 cycle output from another oscillator into an audio-mixer, where external modulation of the stimuli took place before being fed to the two ears.

*Results.* The results of this experiment are presented in Table 3. Examination of this table shows that the raw score means of the experimental group are closely parallel to those of the control group, indicating that there is no appreciable change in test scores produced by either the pure tone stimulus from a single sound source, or the externally modulated beating stimulus (9). The F and t-tests on initial score differences in *Session I* indicate sat-

TABLE 3

RAW SCORE MEANS FOR THE MacQUARRIE TEST FOR MECHANICAL ABILITY ON SESSION I (NO SOUND STIMULATION), SESSION II (PURE-TONE STIMULATION FROM SINGLE SOUND SOURCE), AND SESSION III (BEAT STIMULATION WITH EXTERNAL MODULATION)

| Group | Session | | |
|---|---|---|---|
| | I | II | III |
| Experimental | 77.87 | 84.25 | 96.63 |
| Control | 77.75 | 85.63 | 97.25 |

isfactory matching of the groups. The t–tests computed on the score differences between the various sessions show conclusively that there are nosignificant performance differences produced by either of the auditory stimuli used in this second experiment.

## DISCUSSION

These experiments have involved four types of binaural stimuli: (1) a stimulus generated by two oscillators tuned to the same frequency (Experiment One, *Session II*,) (2) a stimulus generated by two oscillators differing in frequency by eight cps (Experiment One, *Session III*,)(3) a stimulus generated by one oscillator (Experiment Two, *Session II*), and (4) a beating stimulus generated by two oscillators differing in frequency by eight cps and modulated externally in an audio–mixer (Experiment Two, *Session III*). Performance decrement was produced in both sessions of Experiment One with no decrement occurring in either session of Experiment Two.

Considering that the frequency relationship between the binaural tones in *Session II* of the first experiment could not be held completely constant due to the limits of stability of the equipment, one interpretation of the circumstances producing performance decrement in this study is as follows: *Performance decrement occurs when inputs to the two ears differ in frequency, and consequently in phase relationship.* The question now arises as to how the central nervous system is affected by such stimulus conditions.

One good possibility seems to be that tones that differ binaurally in frequency and phase characteristics produce some central neural interaction as a result of the differing afferent inputs arriving simultaneously at some common center. It is this neural interaction that is felt to be responsible for the production of beats of central origin resulting when binaural tones differ sufficiently in frequency as in *Session III* of Experiment One. This view of how afferent inputs of different frequency are presented centrally is consistent with the theories of excitation and conduction in sensory nerves offered by Hill (6), Rashevsky (10), and Wever (13).

The remaining problem is the means by which this hypothesized central interaction process can result in performance decrement. The presence of subjective beats readily suggests that the neural process of hypersynchrony may be responsible for the decrement. This term is used in the same sense as Jasper uses it, meaning large neural potentials having periodic form (7). These repetitive potentials are considered to be opposed to adaptive behavior in that they tend to disrupt or negate the normal synchrony of the discharge pattern in neighboring neural centers or areas. Hebb, for example, discusses the way that hypersynchrony could produce central nervous system disruption:

A focus of hypersynchrony must act as a pacemaker that tends to wean transmission units away from the assembly. When hypersynchrony is not great, it would allow some assemblies to function (particularly those that are long established: p. 197) but would tend to interfere with recent memory, decrease responsiveness, and interfere with complex intellectual activities (5, p. 283).

This is the suggested mechanism by which certain forms of binaural stimulation produce performance decrement. Such a hypothesis is made more attractive since the frequency of the binaural beats employed in this experiment (eight per second) closely approximates the frequency of the normal alpha rhythm. Here it should be noted that the phase shift reported in Session II of Experiment One approximates a harmonic frequency of the alpha rhythm. This is mentioned because of the possibility that a binaural beat of this frequency or a harmonic might, then, more readily produce a disruptive hypersynchrony.

It is interesting to note that there is a remarkable difference in the subjectively experienced quality of beats produced externally in the audio-mixer as compared with those beats generated centrally. The two kinds of beats also were perceived as differentially disruptive by the subjects. Contrary to what would be expected on the basis of the data, the subjects in Experiment One said they felt that the stimulus in neither session bothered them in any way, especially in terms of their performance on the tests. They ignored the fact that they were not doing any better in consecutive performances; in fact, that they were actually doing somewhat poorer. In Experiment Two, however, the subjects invariably reported that the sound in Session III (the externally produced beat) really bothered them and they were sure that their performance was affected. This was in spite of the fact that they could observe that they were completing more items and 'doing better' than they had on the previous sessions. This observation seems to argue further against the purely irritative aspects of sound stimulation as a factor in performance decrement. Apparently, the neural mechanism through which binaural beats influence performance is not open to correct subjective evaluation.

## SUMMARY

A study was designed to determine the effects of binaural interaction, produced by binaural beat stimulation, upon certain performance measures. The hypothesis tested was that binaural beat stimulation would produce an interaction process in the central nervous system with resulting performance decrement. The results indicate that binaural beats do disrupt and hinder certain kinds of performance. A theoretical explanation involving disruption of the normal pattern of nervous system activity by hypersynchronous dis-

charge is suggested as the mechanism by which certain forms of binaural stimulation, having periodic form, produce performance change. The fact that the binaural beats in this experiment were eight per second raises the possibility that the neural mechanism may be related to the normal alpha rhythm. Finally, there are indications that this neural process is not available to correct subjective assessment.

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# CONTROLLED READING RATE UNDER DELAYED SPEECH FEEDBACK

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Renowned among the early investigators of the delayed auditory feedback phenomenon are Lee (9), Azzi (1), Fairbanks (5) and Black (2). Fairbanks (4) has also postulated a theory of automatic control of the act of speaking related to certain principles found in electronic servosystems. It seems entirely feasible that the speaker may utilize information from his output to exert a type of instantaneous control over his speech performance during the act of speaking. When the feedback information is appropriately amplified and delayed, the speaking system is misinformed about its performance and the output is altered.

No studies have been reported to date concerned with controlled reading rate as an independent variable under delayed speech feedback. Reading rate is influenced by the size of the delay interval and several other factors. Therefore, it seems feasible to investigate the influence of various reading rates holding rate and delay interval constant while employing optimum amplification of the feedback signal to enhance the speech disturbance. It seems logical to expect that a decrease in rate should result in less speech errors and if the process is continued the talker will reach a reading rate free of any speech errors. Thus, it should be possible to determine the maximum reading rate for an error free reading under optimum delayed feedback conditions. Portions of this paper were taken from an unpublished thesis by Byers (3) which was performed under the supervision of the author.

## PROCEDURE

*Subjects.* Twenty white young adult college males, ranging in age from 18-26 years, participated in the experiment. The average age of the group was 22.0 years. They were screened for hearing loss, speech and voice defects and the presence of any strong regional dialect. All subjects reported a negative history of neurological injury at birth. The subjects read a test passage under .2 sec. delay within 18-26 seconds with three-six error words.

*Test Passage.* A specially prepared prose paragraph consisting of 98 words was read, the paragraph, referred to as the rainbow passage (6), has been widely used in reading rate studies. The first and last sentences were omitted from analysis to avoid the possible effects of initiating the reading and anticipation of the end of the reading task. The analysis dealt with the intermediate 55 words.

*Apparatus.* A locally constructed delayed auditory feedback system was used (8). The basic component was a commercial magnetic tape recorder, Pentron, model TR-4. Three Pentron heads were used to accomplish the recording, reproducing and erasing processes. In this system, the magnetic tape first encounters an erase head, then a record head and then a reproduce head. Linear tape velocities of 7.5 and 3.75 per second yield delay intervals of .2 and .4 seconds. For this particular experiment, the original pre-amp was replaced by a high quality McIntosh pre-amp, model 30 W-2, The output from the tape recorder was fed into a Grason-Stadler, model 1160-A, speech audiometer. This permitted calibrated attenuation of the delayed feedback signal to the subject's earphones.

*Procedure with Subjects.* The subjects were seated in a straight-backed chair in a sound treated laboratory room. The microphone was placed on a boom swing type arm four inches from the speaker's lips at a right angle to his breath stream. An adjustable head rest was used to maintain a constant lip-microphone distance. The binaural headphones, model PDR-10 were mounted in donut cushions and placed securely over the subject's ears to provide a good acoustic seal.

Each subject read a test passage twice without delay followed by a practice delay reading. They were then instructed to read as they normally do three times. The mean number of errors and the mean duration of the passage were computed for the second and third readings. This reading will be referred to hereafter as the normal, delayed reading. Twenty subjects were chosen who met the prescribed criteria.

*Experimental Readings.* A superior male speaker read the rainbow passage under delayed feedback four times without speech errors at predetermined rates of 132, 96, 72 and 60 w.p.m. respectively. These target rates were selected after preliminary experimentation and were judged to be perceptually different as to rate.

The experimental readings by the subjects consisted of two series; one decreasing and the other increasing in rate. The subject listened to the reference reading and attempted to approximate the reading rate under delayed feedback. Half of the subjects read at the increasing rates first followed by the decreasing rates, while the remainder read at the decreasing rates first followed by the increasing rates.

## RESULTS

The objectives of this study were to determine a maximum error free reading rate under delayed speech feedback and to examine its theoretical implications. It was hypothesized that articulation errors would decrease as reading duration increased. It was further hypothesized that a reading

rate would be reached which would not include any articulation errors. The results support each hypothesis.

Comparison of the normal, delayed readings and the error free delayed readings showed the following. The mean duration of the normal delayed readings was 21.65 seconds with a mean of 4.53 errors. The mean of the maximum error free, delayed readings was 39.94 seconds. A $t$ value between the mean errors was significant beyond the .01 level. However, since the homogeneity of variance for zero errors can be questioned, a non-parametric sign test was computed yielding a $z$ of 4.24 significant beyond the .01 probability level.

In Figure 1, the mean error words for each reading are plotted as a function of duration for the normal delayed reading and each of the four con-

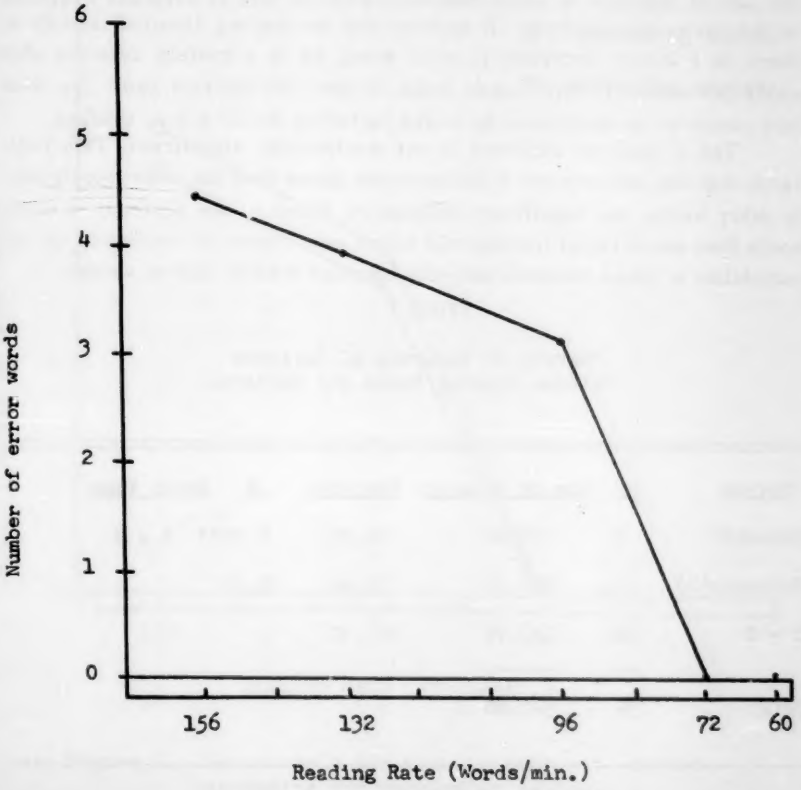


Figure 1. Mean error words/reading rate under delayed feedback.

trolled readings. A *t* test for the significance of the difference between the means of the 96 w.p.m. readings and the 72 w.p.m. readings was computed. A *t* value of 7.50 was obtained which is statistically significant beyond the .01 level for 38 degrees of freedom. A non-parametric sign test yielded a *z* of 4.24 and is also significant beyond the .01 level. The mean w.p.m. error free reading occurred when the subjects read at 84 w.p.m.

In Table I, the results of an analysis of variance are displayed. The analysis was suggested by Lindquist (10). The F ratio for articulation errors occurring at levels of reading rate is statistically significant at the .01 level. Thus, as rate decreases, there is a gradual decrease in errors from the normal delayed reading to the 96 w.p.m. reading. From the 96 w.p.m. reading to the 72 w.p.m. reading, there is a marked acceleration in the rate of decrease in errors compared with the rate of decrease exhibited in the faster reading rates. It appears that as reading duration increases, there is a steady decrease in error words up to a certain duration after which the number of error words drops to zero. Beyond this point ,the error free condition is maintained up to and including the 60 w.p.m. reading.

The *F* ratio for subjects is not statistically significant. This indicates that the subjects are a homogeneous group from the same population. In other words, the significant differences found in the decrease of error words from one level of reading rate to the next cannot be attributed to the variability in errors between subjects from one reading rate to another.

TABLE I

Summary of Analysis of Variance
Between Reading Rates and Subjects

| Source | df | Sum of Squares | Variance | F | Error Term |
|---|---|---|---|---|---|
| Rates(R) | 2 | 96.60 | 48.30 | 8.79** | R x S |
| Subjects(S) | 19 | 234.80 | 12.40 | 2.25 | |
| R x S | 38 | 208.60 | 5.50 | | |
| Total | 59 | 540.00 | | | |

**F, df 2 & 38: .01 level, 5.21

F, df 2 & 19: .05 level. 3.52

In Figure 2, the ascending and descending series are plotted for comparison of the errors in each reading. In order to determine the homogeneity of the errors for the two series for the 132 and 96 w.p.m. readings, an analysis of variance was computed. The results are shown in Table 2. The 72 and 60 w.p.m. readings were omitted since they contain no error words. The *F* ratio for the two series is non-significant and less than one, which supports the assumption that the two series are homogeneous.

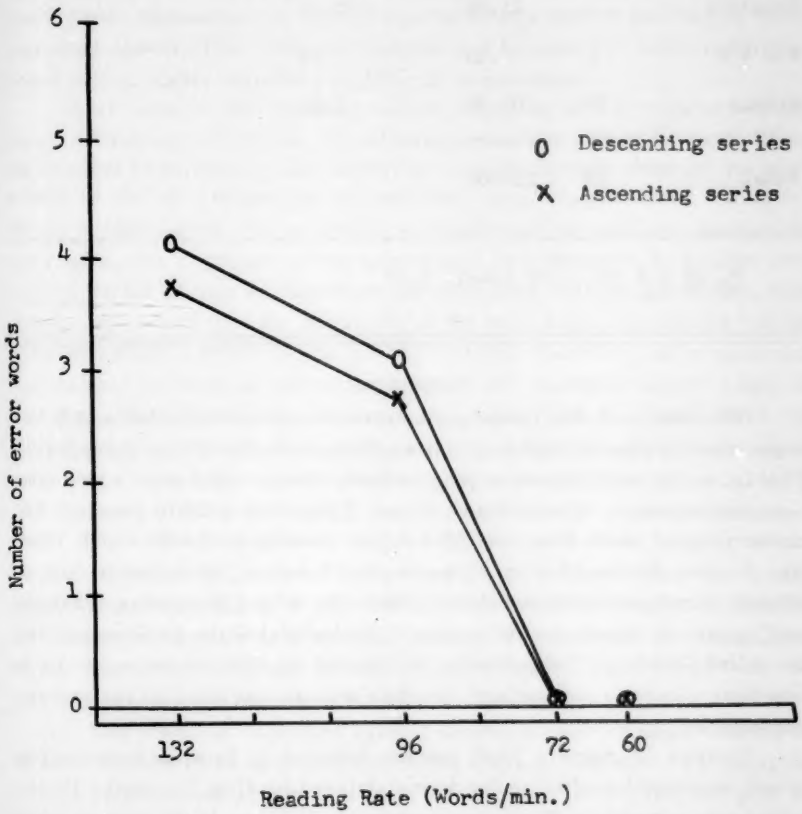


Figure 2. Error words for each reading rate in the ascending and descending series.

TABLE 2

Summary of Analysis of Variance Between the Ascending and Descending Reading Rates

| Source | df | Sum of Squares | Variance | F | Error Term |
|---|---|---|---|---|---|
| Ascending-Descending(A-D) | 1 | .60 | .60 | 1.0 | Within |
| Rates(R) | 1 | 21.00 | 21.00 | | |
| A-D x R | 1 | .10 | .10 | | |
| Within | 76 | 92.30 | 1.21 | | |
| Total | 79 | 114.00 | | | |

F, df 1 & 76: .05 level, 3.97

## DISCUSSION

The results of this investigation revealed an inverse relationship between reading duration and error free words under delayed speech feedback. That is, as the subject read at progressively slower rates there was a concommitant decrease in articulatory errors. There was a fairly constant decrease in error words from the 152.4 w.p.m. reading to the 96 w.p.m. reading. As rate decreased from 96 w.p.m. to 72 w.p.m., error words dropped sharply to zero and remained there down to the 60 w.p.m. reading. When the reading rate is slower than 60 w.p.m. it is doubtful if the performance can be called 'reading.' Subjectively, it seemed to this experimenter to be something closer to singing and therefore was not included in the present investigation.

Guttman (7) found a 30-40 percent increase in duration between the normal, undelayed reading to the normal delayed reading. Fairbanks (5) reported approximately a 40 percent increase in duration. In the present study there was a 31 percent increase in duration from the normal, undelayed reading to the normal, delayed reading. All three investigators used the same reading material. One probable reason for differences in increases in reading duration may be the criteria used in the selection of the subjects. The present investigation used a homogeneous group of subjects equated for reading rate and disturbance under delayed speech feedback.

## THEORETICA L CONSIDERATIONS

According to Fairbanks (4), when the speaker reads under delayed speech feedback, it might be said that the feedback signal misinforms the speaking system about its success in effecting and in ordering its intended output units, thus impairing its basic product.

When the subject is instructed to read under delayed speech feedback at progressively slower rates, he soon reaches a rate where he can overcome his articulation errors. Essentially, this is accomplished at the expense of a considerable increase in the duration of his speech sounds above that found in undelayed, normative reading rates. His maximum, error free reading rate approaches the rate of conversational speech and may be even somewhat slower. This latter comparison is a tenuous one since conversational rate is highly variable and difficult to normalize.

If we consider the speaking system operating as a servosystem under delayed feedback conditions, the following explanations may be made. When the speaker is performing, the corrective changes brought about by the magnitude of the error signal are slower than those brought about during reduced reading rates. For example, in rapid reading rates as opposed to slow rates, the magnitude of the error signal is comparatively smaller over a given period of time and therefore the corrective changes are slower. The reader will recall that the magnitude of the error signal determines the degree of change exerted by the control system. Therefore, as reading rate increases, the rate of corrective changes are probably slower since the speaker accomplishes his unit tasks at a faster rate. At slower rates, the corrective changes are more rapid since the magnitude of the error signal persists over a longer period of time. This interpretation may account for the decrease in errors as reading rate decreased in the present study.

We may also hypothesize that the speaking system no longer operates under the major influence of delayed auditory feedback when the speaker reads uninterruptedly at a rate which is less than his maximum error free reading rate. One notes a parallel between the stutterer who attempts to speak in monosyllables and the subject under delayed speech feedback who reads at a slow rate to escape the effects of delay.

The reader is cautioned against making a close analogy between impromptu speaking and specified controlled reading. The act of speaking involves reproduction at one point either exactly or intelligibly an input selected at another point. The actual input is one selected from a set of possible inputs. Thus, the speech system is designed to operate for each possible selection; not just the one actually chosen, since this is unknown before the time of selection. This is the general status of impromptu speech. The occurrence of speech sounds is subject to probability laws which are in turn dependent about 50 percent of the time on past selections according

to Shannon and Weaver (11). This is not the case when reading a familiar, prescribed passage. In a prescribed reading passage, familiar to the reader redundancy is extremely high and the amount of information transmitted is low. The reader's task is therefore easier.

## SUMMARY

Twenty white young adult males were instructed to read a test passage at various reading rates under optimum conditions of delayed speech feedback. The subjects were carefully screened for speech, hearing and voice defects and the presence of a strong regional dialect. They were equated for degree of speech disturbance and reading rate under delay. They were instructed to read at 132, 96, 72 and 60 words per minute in order to reach an error free reading.

As reading rate decreased, error words decreased until the articulatory errors reached zero. The mean maximum error free reading rate was 84 words per minute. Analogies were made to the speaking system operating as a servosystem. It was hypothesized that the corrective changes exerted by the control system, if it exists, are more rapid for slower reading rates than for faster reading rates.

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# ALTERATIONS IN THE PURE TONE THRESHOLD FOLLOWING CHANGES IN BOTH ABSOLUTE AND DIFFERENTIAL PRESSURES UPON THE EAR

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## ABSTRACT

A reduction in absolute pressure in conjunction with the application of higher and lower differential pressures to the external ear alters the pure tone threshold of hearing. In general, the threshold is raised with increase in pressure change. The effect varies also with the frequency of the tone.

## INTRODUCTION

The purpose of this investigation was to ascertain the major changes in pure tone acuity at various frequencies due to application of both relatively higher and lower pressures on the tympanic membrane at sea level and at simulated altitude.

There are several operational circumstances in aviation which may result in differences in gas pressure between the middle ear and the ambient pressure in the external auditory canal during flight. The more common situation arises from blockage of the Eustachian tube during descent from altitude which prevents equilibration of pressure in the middle ear cavity with the increasing ambient pressure. The opposite situation may occur, however, under conditions of forceful efforts to relieve Eustachian block, or during positive pressure oxygen mask breathing wherein relative increase of pressure within the middle ear may be created.

The effects upon hearing of differential pressure stress across the tympanic membrane have been investigated at absolute pressures near sea level by Mach and Kessel (1), Loch (2), Rasmussen (3), and many others. In general, it has been found that, with increase of positive pressure on the external surface of the tympanic membrane, there is a decrease in loudness (raised or increased threshold) in the middle frequency range, and irregular results have been noted in the higher frequencies. Rudmose, *et al* (4) found that the shift in threshold of hearing between sea level and 35,000 ft was within the limits of experimental error (2.5 db) when temperature remained constant. However, the parameter of reduced barometric in addition to, and

Opinions and conclusions contained in this report are those of the authors and do not necessarily reflect the views or endorsement of the Navy Department.

coincident with, differential pressures across the tympanic membrane has not been investigated.

## PROCEDURE

*Subjects and Method*

This investigation was conducted upon three male volunteer human subjects 19 to 21 years of age, each of whom was known to have normal binaural hearing and normal intact tympanic membranes as determined by screening examination conducted by an otorhinolaryngologist in advance of the experiment.

The basic apparatus employed in this study consisted of an airtight plastic cup which was clamped snugly over the left ear and sealed with a soft rubber gasket to prevent excessive leakage. Higher (positive) or lower (negative) pressures than ambient were produced within the cup and consequently upon the external surface of the eardrum by a compressor or vacuum pump, respectively, as the occasion required. Pressures in the cup were controlled by needle valves and measured by a water manometer. It will be noted that an increase in positive pressure within the middle ear cavity relative to pressure in the external auditory canal as occurs in pressure breathing is synonymous in effect to negative differential pressure as considered in this experiment.

Reduction in absolute pressure was produced by means of decompression in a low pressure chamber. Chamber pressure equivalent altitudes of sea level and 30,000 ft were imposed in addition to which both positive and negative pressures up to 10 in of water were produced within the cup.

A calibrated earphone (Permaflux PDR–8) and a condenser microphone (Altec 21–D) were incorporated within the ear cup for pre–experimental testing of the apparatus to determine the effect of atmospheric pressure changes on the response characteristics of the transducer. Correction factors were computed from the resulting observations for calibration purposes to ensure that the output of the transducer was known throughout the experiment.

The test tone frequencies studied in the experiment were 100, 250, 500, 1000, 2000, 4000, and 7500 cycles per second. The major portion of the energy in speech sounds are found in the frequency region approximately between 250 and 2000 cps. These test frequencies were generated by an oscillator which fed a power amplifier. The output of the amplifier, in turn, was connected to the input of a recording attenuator (Grason–Stadler Model E3262A), and the output of the attenuator was then fed to the subject's earphone. The recording attenuator recorded the tone attenuation necessary to

obtain a threshold of perception at each test frequency under both normal and experimental conditions. The effect of the variation in pressure was then determined by comparison of the attenuator recordings. (Fig. 1 is a schematic diagram of the stimulus presentation equipment and the response-indicating instrumentation.)

Through use of an auxiliary pump located some distance from the low pressure chamber, the noise level from this source was maintained definitely below the interference level of the tone frequencies used. The noise from the operation of the oxygen masks within the chamber was reduced by having the subject and inside observer breathe slowly and by the attenuation of the ear cup. The right ear which was not being tested was, in addition, protected from chamber noise by a foam rubber cup.

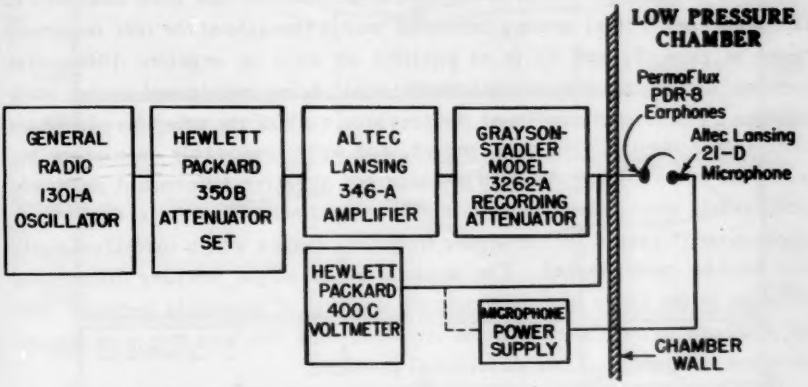


Figure 1. Schematic Diagram of Instruments Used to Measure Pure Tone Threshold in Low Pressure Chamber.

To minimize the error due to variation in the time taken by the subject in pushing the button when threshold was reached, repeated determinations were made on each individual at each test frequency, and the mean values were recorded. In addition, at least five min. were allowed for equalization of pressure in the middle ear after ascent to simulated altitude to minimize the possibility of differential pressure effect across the tympanic membrane due to lagging equilibration of pressure in the middle ear with ambient pressure. It must be emphasized, however, that while the time for pressure equalization seemed to be ample, there was no positive way of observing or measuring the direction or amount of displacement of the tympanic membrane

It was necessary, therefore, to rely upon the subjects' own impressions that equalization had taken place and thus infer that the Eustachian tube remained patent. Although the level of discomfort from application of differential pressures across the eardrum varies widely (some subjects report discomfort at pressure differentials as low as 15 in of water, 0.54 psi, while others tolerate differentials well in excess of 1.0 psi), the modification of threshold acuity observed did not correspond to sensation of discomfort.

Because of chamber leakage and the admission of room air in ventilation, the temperature drop which followed evacuation of the chamber returned within one degree Centigrade of room temperature by the time equilibration in pressure was allowed for the middle ear cavity.

## RESULTS

As a preliminary study, two of the three subjects had been measured to determine their actual hearing threshold levels throughout the test frequency range at zero, 5, and 15 in of positive as well as negative differential pressure across the tympanic membrane while being maintained at sea level pressure. The results confirmed the previous work of the other investigators cited in the introduction, as expected, and were reasonably consistent between the two subjects. As both positive and negative differential pressures increased in magnitude from zero, the hearing thresholds were also progressively raised* except for the higher frequency ranges where individual variation became more marked. The application of slight positive differential pressure in the range of 5 in produced lowering of threshold between 2000 and 4000 cps in one case, while in the other case this was true with the application of slight negative differential pressure.

It was considered from these observations that maximum positive and negative differential pressure magnitudes of 10 in of water (0.36 psi) as compared to zero differential pressure were sufficient to modify unequivocally the threshold of acuity for the specified pure tone frequencies employed in this study. Accordingly, these values, which were below the range of discomfort, were selected for the purposes of this investigation as the pressure modifications for all three subjects both at sea level and at 30,000 ft chamber pressure altitude equivalents.

*For the sake of clarity it is desirable to emphasize that an increased or raised threshold at any given frequency is synonymous with a hearing acuity loss at that frequency. The data resulting from the present study are graphically represented as differences from given baseline comparison conditions rather than in the form of absolute threshold values. It will be noted that change is accordingly indicated in either a positive or negative direction; thus, a negative datum at any given frequency represents a hearing loss at that frequency as compared with the baseline condition specified, and conversely, a positive datum represents a hearing gain.

For an experimental framework were selected the conditions ranging from 10 in negative differential pressure through zero to 10 in positive differential pressure, compared at both sea level and 30,000 ft simulated altitude; and each subject's threshold response was then measured on the recording attenuator.

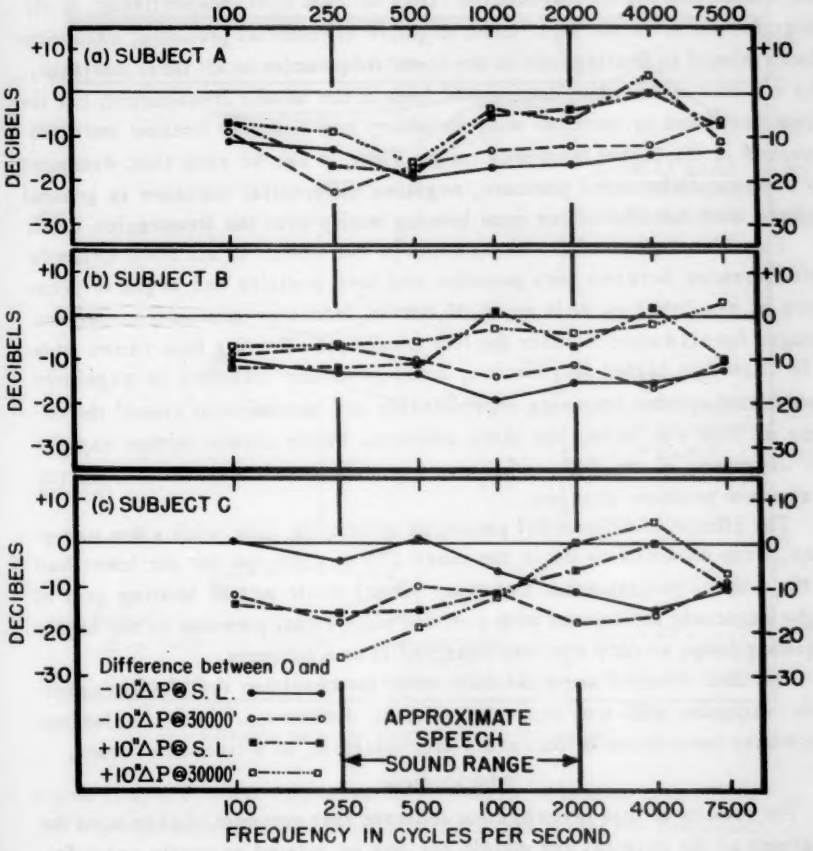


Figure 2, a, b, and c. Attenuation of Hearing for Each Subject Following the Application of Pressures Across the Tympanum.

In Fig. 2, a, b, and c the curves for difference between zero pressure and both positive and negative differential pressures of 10 in magnitude at sea level as well as at 30,000 ft for each individual indicate that hearing loss occurred at nearly every frequency in all subjects when differential pressures were imposed across the eardrum. It is interesting to note that positive differential pressure was associated with greater hearing loss in the lower frequency range (100 to 1000 cps). However, hearing loss tended to be minimal and even approached normal values or actual hearing gain in the middle and higher frequencies (1000 to 7500 cps), respectively, in all three subjects. On the other hand, negative differential pressure, while similarly related to hearing loss in the lower frequencies in all three subjects, did not tend to minimize associated loss in the middle frequencies; but the loss continued to increase with frequency and possibly became more pronounced in the higher frequency range. Thus, it can be seen that, compared to positive differential pressure, negative differential pressure in general had the more adverse effect upon hearing acuity over the frequencies used.

Fig. 3, a, b, c, and d which compares the curves of all three subjects for differences between zero pressure and both positive and negative pressures at sea level as well as at 30,000 ft. indicates generally consistent changes for all subjects under the four conditions. Hearing loss varies widely in degree at higher frequencies, being generally lessened in magnitude around 2000 cps but becoming unpredictable and inconsistent around the extreme at 7500 cps among the three subjects. These curves further suggest that the trends of the differential pressure differences may not be affected by absolute pressure changes.

The effects of differential pressures on hearing loss, with a few exceptions, were observed to lie in the range 250 to 1000 cps (or the lower half of the voice communication frequency range) while actual hearing gain of slight magnitude associated with positive differential pressure in the higher frequency range at 4000 cps was observed in two subjects.

The data obtained are valid only under the condition that the uncontrollable variables did not cause significant distortions. The conclusions which have been drawn in this study are, therefore, of a tentative nature.

## DISCUSSION

The results of this investigation indicate that pressure change upon the apparatus of the external and middle ear may be related at nearly every frequency to an increased threshold of auditory acuity (i.e., hearing loss). This is particularly true in the useful voice communications range of 256 to 2048 cps. The effect at altitude is essentially the same as at sea level. An increase in sound intensity in the order of 20 to 30 db magnitude would ap-

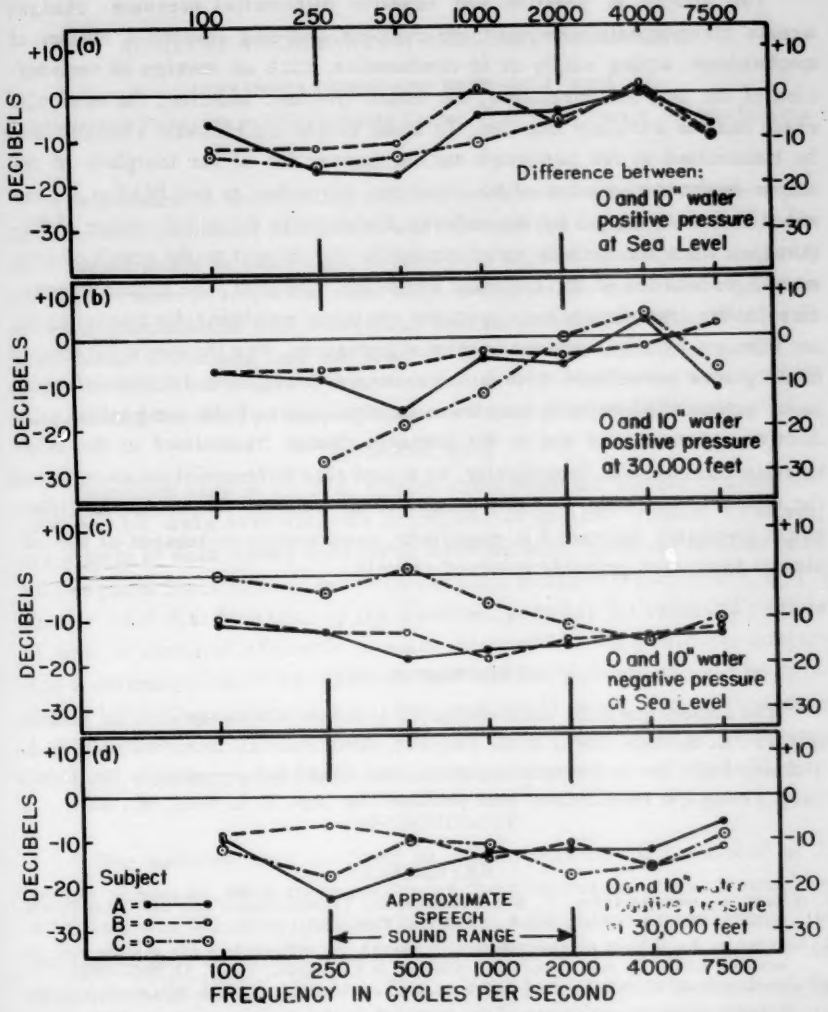


Figure 3, a, b, c, and d. Comparison of Attenuation of Hearing AmongThree Subjects Following the Application of Pressures Across the Tympanum.

parently compensate for this loss at all altitudes, up to and including 30,000 ft, when differential pressures across the tympanic membrane do not exceed a positive or negative 10 in of water pressure.

The effects of positive and negative differential pressure changes across the tympanic membrane are complex and may involve a number of mechanisms, acting singly or in combination, such as tension or compression of the tympanic membrane, the tensor tympanic muscles, the ossicular chain and the ancillary muscles. To some extent the pressure changes may be transmitted to the perilymph via the connection of the footplate of the stapes to the oval window of the inner ear. According to von Békésy (5), the minor variations shown by the auditory threshold in the middle range of frequencies when the drum is under tension is due in part to the result of segmental resonances of the tympanic membrane. However, the higher frequencies having less dependance upon the tympanic membrane for transmission are affected less by such application of pressures. Van Dishoeck (6) related hearing loss associated with both positive and negative differential pressures across the tympanic membrane to impairment of the mechanical conductive apparatus and not to the pressure change transmitted to the labyrinthine fluid system. Specifically, he stated that differential pressure across the tympanic membrane initially dampened the eardrum vibrations; as differential pressures increased in magnitude, compression or tension of the ossicular chain was probably involved as well.

## ACKNOWLEDGMENTS

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# AUDITORY DISCRIMINATION AND SLEEP DEPRIVATION

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## ABSTRACT

Performance on an ABX task requiring the discrimination of differences in tonal frequency, intensity, and duration was measured four separate times each day for a four-day period in which eight subjects were deprived of sleep. As compared with data obtained at comparable times under nondeprivation conditions, significant losses in discrimination were noted which first became apparent after 32 hours of wakefulness. A maximum loss was found at 48 hours with subsequent partial recovery toward the end of the deprivation period. Greater impairments were noted in discriminating frequency as compared to intensity and duration differences .

## INTRODUCTION

Previous studies (1, 2, 4, 6) have considered the effects of sleep deprivation on tasks involving the perception of auditory stimuli. However, the effects of such stress upon tonal discrimination seem not to have been investigated. Since current and proposed uses of auditory displays (5, 6, 10) require tonal discrimination by the observer, possibly for extended periods of time, it appeared advisable to study this problem. Of particular interest was a determination of the length of time that discrimination could be maintained before impairments due to sleep loss would occur. Also of importance was whether the discrimination of different tonal dimensions, i.e., frequency intensity, duration, would be differentially affected by sleep deprivation.

## METHODOLOGY

The auditory task involved an ABX procedure. It consisted of 72 groups of sounds, each group containing three successive tonal bursts. The third tone was identical to either the first *or* second tone in each group, the unmatched tone differing in variable amounts of frequency, intensity, *or* duration from the identical tones. The subject had to indicate which of the first two tones matched the third. Four values of frequency (1000, 1010, 1020, 1030 cps), intensity (70, 73, 76, 79 db re 0.0002 dyne/cm$^2$) and duration (1.0, 1.3, 1.6, 1.9 sec.) were used in constructing the tonal groups. There were 24 tonal groups in which the unmatched tone differed in frequency from the other two tones, 24 in which it differed in intensity, and 24 in which it differed in duration. The unmatched tone was varied to give all possible differences for each tonal dimension and was counterbalanced in terms of the first and second position in the tonal group.

The variable frequency settings were obtained with a calibrated Krohn-Hite push-button oscillator (310-AB) whose output was supplied to a MacIntosh pre-amplifier (C-104) and power amplifier (A-116). The amplified signals were fed to a set of five Hunter interval timers (111C) and then taped on a Concertone tape recorder (Model 504). The four duration values were determined by adjusting the interval settings on the timers. The timers also controlled a .5 sec. interval between the three tones comprising each group. Relative intensity settings were initially made with the use of a Ballantine vacuum-tube voltmeter (Model 300). Subsequently, the playback level of the recorder was set to produce an earphone output which gave the four sound pressures (within $\pm 1$ db) cited above as measured in a 6cc coupler. Four permutations of the 72 groups of sounds were taped and used in the study. About 18 minutes were necessary to run through each permutation.

Eight white enlisted men who were thoroughly-familiarized with the task served as subjects. Different permutations of the task were given at 3 A.M., 8 A.M., 4 P.M., and 11 P.M.[1] on each of four successive days in which the men were deprived of sleep. Group tests were used, the tones being fed binaurally through eight sets of PDR-8 earphones mounted in doughnut cushions. When they were not being tested, the subjects were kept busy with television, games, and craft kits. During the entire deprivation period, the subjects were carefully watched to insure that they did not doze off.

One month after the deprivation tests, the same subject group was retested under non-deprivation or control conditions. The tests were given at 8 A.M., 4 P.M., and 11 P.M. for a period of four successive days. For obvious reasons, no control test was given at 3 A.M. Therefore, the results which follow do not consider control-experimental comparisons at 3 A.M.

## RESULTS AND DISCUSSION

Scores on the auditory discrimination test, expressed as the median percentage of 72 items which were responded to correctly by the subject group under control and sleep deprivation conditions, are shown in Figure 1. As expected, little or no differences exist between the two sets of data for the first day. Beyond Day 1, however, the deprivation and control curves diverge, the deprivation scores showing a loss in discrimination as compared

[1] On the fourth day of deprivation, the test was given at 10 P.M. rather than 11 P.M.

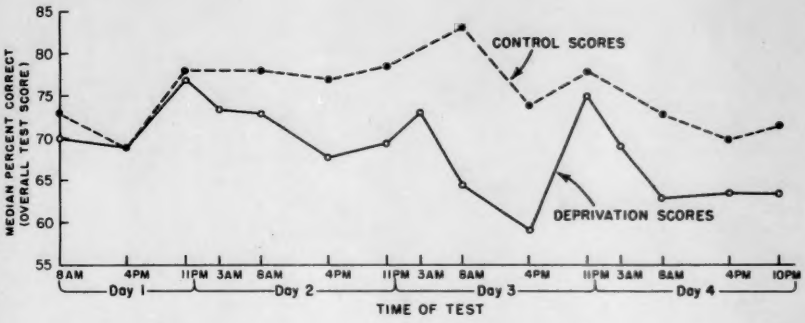


Figure 1. Median percent of correct responses for subject group on tonal discrimination test given at specified times during the sleep deprivation and control periods.

with the control values. Non-parametric statistical analyses[2] of the differences between control and deprivation scores indicated that a significant loss in discrimination first occurred at 4 P.M. on Day 2, i.e., after 32 hours of wakefulness. The impairment, however, did not show a systematic tendency to become greater with increasing amounts of sleep loss. Rather, a maximum loss (18%) was reached at 8 A.M. on Day 3, i.e., after 48 hours of wakefulness, followed by a partial recovery toward the end of the deprivation period. With respect to time of test, the decrements noted at 4 P.M. were significant on Days 2, 3, and 4. The losses at 8 A.M. and 11 P.M. were significant only on Days 3 and 2 respectively.

In Figure 2 are plotted the discrimination losses (differences between control and deprivation scores) for each subject for different times during sleep deprivation. Each subject's function shows discrimination losses whose magnitudes fluctuate widely across the deprivation period. As typified by the medians shown in Figure 1, however, most subjects' data show the greatest losses in discrimination midway through the four-day period followed by partial recovery at the end of the experimental session. The marked fluctuation exhibited by the individual curves is probably reflective

[2] All differences between control and deprivation scores were evaluated for significance by sign tests (9). A K-sample test against ordered alternatives (8) was used in evaluating the significance of trends. The probability required for significance in all tests was $p < .05$.

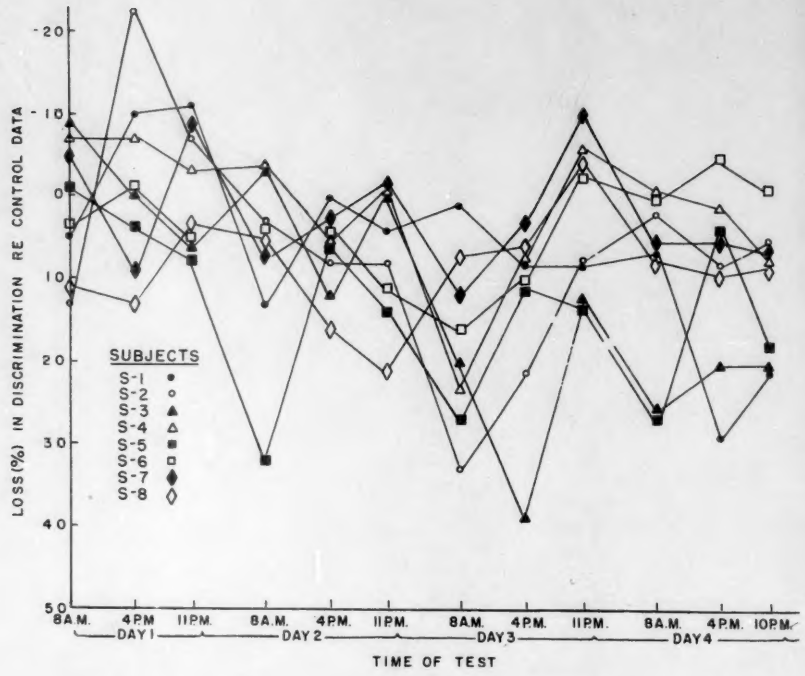


Figure 2. Losses in discrimination for each subject at specified times during sleep deprivation.

of diurnal variation. While such variation would also tend to occur under control conditions, it seemingly would become more enhanced under the conditions of sleep loss. The improvement in performance toward the end of the deprivation session is more difficult to explain. Presumably, it is not due to learning since the subjects were thoroughly trained on the task prior to the experiment. There is also evidence from another study (3) which negates the presence of a learning effect with repeated administrations of this task. The recovery may represent adjustments of the subjects to the stressful situation.

The losses in deprivation scores when compared to control data are shown for each of the variable dimensions of the unmatched tone in Table I. The magnitudes of impairment for each dimension vary from test time to test time but generally reveal greater losses for frequency than for intensity and duration cues. Statistical evaluations indicated significant losses for frequency, intensity and duration cues on 6, 4, and 2 occasions of testing respectively. While these results suggest that sleep loss differentially af-

Table I

Differences between median percentage scores for control and deprivation conditions by dimension of unmatched tone and time of test

| Time of Test | Frequency | | | Intensity | | | Duration | | |
|---|---|---|---|---|---|---|---|---|---|
| | Control | Depriv. | Diff. (Loss) | Control | Depriv. | Diff. (Loss) | Control | Depriv. | Diff. (Loss) |
| Day 1 | | | | | | | | | |
| 8 AM | 83 | 73 | 10 | 73 | 73 | 0 | 62 | 62 | 0 |
| 4 PM | 73 | 71 | 2 | 77 | 67 | 10 | 64 | 69 | -5 |
| 11 PM | 90 | 81 | 9 | 77 | 77 | 0 | 66 | 73 | -7 |
| Day 2 | | | | | | | | | |
| 8 AM | 79 | 64 | 15* | 83 | 75 | 8 | 71 | 62 | 9 |
| 4 PM | 79 | 71 | 8 | 77 | 71 | 6* | 71 | 62 | 9 |
| 11 PM | 90 | 77 | 13* | 77 | 73 | 4 | 71 | 60 | 11 |
| Day 3 | | | | | | | | | |
| 8 AM | 90 | 64 | 26* | 83 | 66 | 17* | 77 | 52 | 25* |
| 4 PM | 85 | 64 | 21* | 71 | 54 | 17* | 66 | 52 | 14 |
| 11 PM | 79 | 77 | 2 | 75 | 77 | -2 | 72 | 66 | 6* |
| Day 4 | | | | | | | | | |
| 8 AM | 85 | 71 | 14 | 73 | 66 | 7 | 62 | 58 | 4 |
| 4 PM | 81 | 58 | 23* | 75 | 62 | 13 | 64 | 66 | -2 |
| 11 PM | 85 | 66 | 19* | 73 | 62 | 11* | 64 | 66 | -2 |

Dimension

*Difference is significant beyond .05 level.

fects the discrimination of various dimensions of a tone, conclusions regarding such an effect must be withheld in view of other aspects of the data. Specifically, discrimination of intensity and especially duration differences under control conditions was poorer than that shown for frequency. This, in effect, might have minimized the chances of obtaining more significant losses for intensity and duration cues under sleep deprivation.

Williams et al (11) have suggested that sleep deprivation will adversely affect performance on tasks having the following features:

1. The presentation of stimuli as well as the time available for response is controlled by the experimenter rather than the subject.

2. The task demands alertness and concentration for comparatively long periods with little or no interruption.

3. There is no immediate feedback information, i.e., no knowledge of results .

The auditory discrimination task used in the present study had each of these attributes which may account for the losses obtained. On this basis, tonal displays of information should not include any of the aforementioned features, particularly if the observer is expected to be on duty for prolonged periods of time.

## SUMMARY

Eight subjects were given an auditory discrimination task four separate times each day during a four-day period in which they were deprived of sleep. The discrimination task required the detection of differences in tonal frequency, intensities, and duration and was of the ABX type. As compared to scores obtained under non-deprivation conditions, significant losses were noted in discrimination which first became apparent after 32 hours of wakefulness. A maximum impairment was noted at 48 hours followed by partial recovery in performance toward the end of the deprivation period. Losses in frequency discrimination were greater than those noted for intensity and duration. This result might have been due to initial differences inthe ability of subjects to discriminate these cues.

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# EFFECT OF STIMULUS RISE-TIME ON RESPONSES EVOKED FROM THE CEREBRAL CORTEX OF THE CAT

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ABSTRACT

The rate at which an auditory stimulus goes from zero to 'steady-state' intensity was found to influence the following response measures: (1) amplitude, (2) slope of the initial wave front, (3) duration, and (4) wave-form, as well as the region of the cortex activated.

In the anesthetized cat the evoked potential at the cerebral cortex to auditory stimulation occurs primarily to stimulus onset. That is, if a sound stimulus is delivered to the cat's ear, after some latent period a stimulus-synchronized response occurs with a duration of perhaps 25 to 100 msec. Ordinarily no response is seen to an on-going stimulus although there is some evidence of very low levels of activity detectable by special techniques (1).

Clicks (DC pulses) have been widely used as stimuli in investigations of potentials evoked in the auditory nervous system (2). Since the ear ordinarily responds only to pressure changes, as far as it is concerned clicks consist almost entirely of onset (and offset) with no steady state. The reason for the wide use of clicks is probably that they evoke very large, stable, and easily observed potentials and that they are easily generated (although difficult to specify acoustically). From the point of view of this report, clicks used in previous experiments have two interesting aspects; they have a very short rise-time and they are rich in harmonics. Ordinarily, these two factors are related; that is: if a waveform has a rapid onset, this implies that energy is spread widely in the frequency spectrum (3). However, if a stimulus is used which in its steady state has energy spread widely in the frequency spectrum, then the rapidity with which it is switched on or off will have little effect on its spectrum. Wide-band-thermal noise is such a stimulus.

It is interesting to ask why large, widespread responses are evoked with click stimulation. Is it because many frequency components are present, each stimulating many neurons, with the result that many fibers fire simultaneously? This multiple firing would presumably summate and be observed as a large response if a gross electrode were used. Or is it that a sudden, abrupt stimulus onset is simply a more effective stimulus in inducing a synchronized discharge (4)? This paper reports some observations on these questions.

Specifically, evoked potentials were recorded from the auditory cortex of the cat in response to pure tones and wide-band noise equated in amplitude, but presented with various rise-times. Approximately 25 cortical points were investigated with about eight responses recorded for each stimulus condition at each point. Cats were anesthetized with Dial, positioned in the head-holder and both cerebral cortices exposed. Sound was produced by an enclosed Permoflux PDR-10 earphone, led to the ear by a polyethylene tube fastened to a speculum which was tied in the external auditory meatus. The tube contained a length of wool yarn in order to minimize resonance effects. The dura was removed from the side contralateral to the ear stimulated and potentials were recorded from this side with either a KCl filled glass pipette or a platinum wire. The indifferent electrode was sewn under the fascia adjacent to the exposed cortex. Potentials were amplified by balanced preamplifiers and displayed and photographed on a cathode ray oscilloscope.

Figure 1 shows the topical distribution of response amplitudes for two stimuli 200 cps and noise. Superimposed upon the region of the suprasylvian, anterior and posterior ecto-sylvian sulci are potential gradient contours. The inner contours contain points with the largest amplitude, while the outer contours contain increasingly smaller responses. Note that at the fast rise-times the response pattern for 200 cps is nearly as large and as widespread as that for thermal noise. However, as rise-time is lengthened, the response area of the 200 cps stimulus is constricted to a much greater degree than for thermal noise. This seems to indicate that constriction of the 200 cps response area is related to the reduced energy spread at the slower rise-times. However, the response area for noise also shrinks as rise-time is lengthened, showing the action of at least one other mechanism reacting to rise-time *per se*. The results for other sinusoidal stimuli (500-10,000 cps) showed results similar to those for 200 cps although constrictions were not quite as marked.

In addition to reducing response amplitude selectively as shown in Figure 1, as rise-time is lengthened several other effects occur. With few exceptions lengthening stimulus rise-time decreases the slope of the evoked response's initial wave front. Moreover, it tends also to increase the response duration. These two effects seem to occur regardless of electrode location or stimulus type. Reduced initial slope and increased response duration are expected effects if the following simple model holds.

As a descriptive model we might assume that a population of neurons exists whose members have non-identical sensitivities; that is, they have sensitivities that are distributed along a continuum of stimulus intensity.

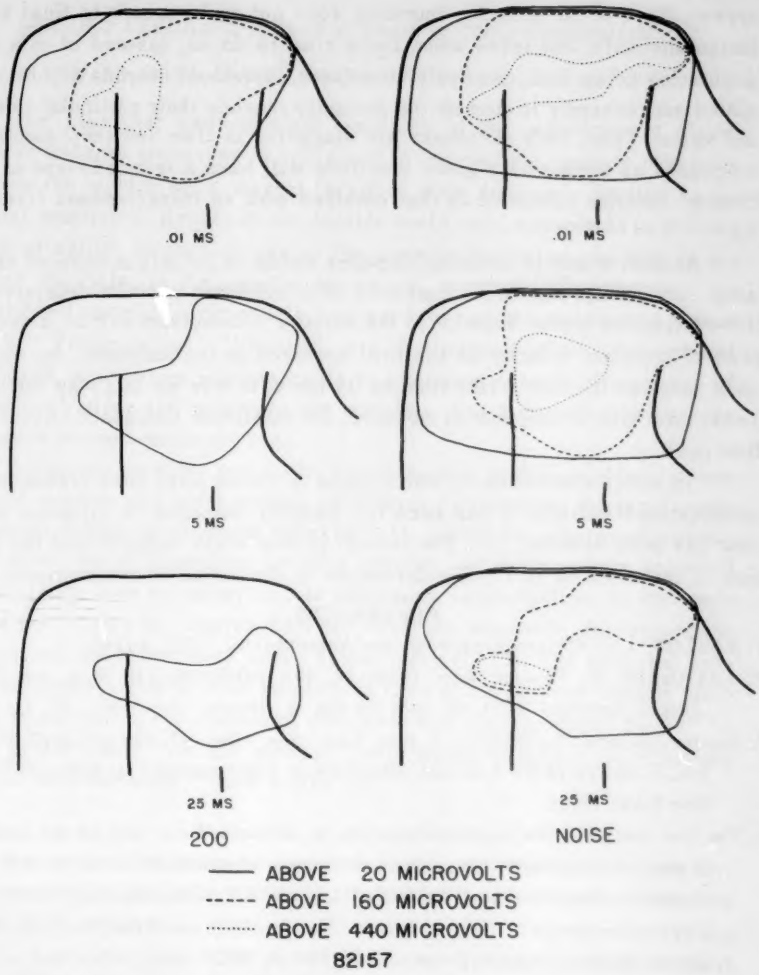


Fig. 1. Potential-gradient contours on the cat's right cerebral cortex evoked by auditory stimuli. The left column is for 200 cps stimulation while the right column shows the results for stimulation by thermal noise. Stimulus rise-time is varied from 0.01 msec in the top row to 25 msec in the bottom row. The data presented are for a single cat, but are typical of the other four cats investigated.

Then, if the stimulus intensity goes instantaneously from zero to some final value, presumably a sub-population of all neurons which respond to intensities equal to, or less than, this final value would be stimulated at that instant. After some period of latency, a stimulus-synchronized response would

appear. Now, if the stimulus intensity does not go from zero to final value instantaneously, but takes some finite time to do so, instead of this subpopulation being simultaneously stimulated, individual neurons will be stimulated successively in time as the intensity reaches their particular threshold value. Thus, their responses are staggered in time and their summated responses as seen with a gross electrode will have a reduced slope and increased duration compared to that obtained with an instantaneous rise-time (5).

Another effect of reducing rise-time seems to be unique to noise stimulation. Ordinarily, responses consisted of monophasic positive defelections. However, in the region superior to the anterior ecto-sylvian sulcus, a second peak of the same polarity as the first appeared in the response. Its amplitude grew until, with a rise-time of 25 msec, it was as large as the first peak, and with a rise-time of 50 msec, its amplitude surpassed that of the first peak.

In most experiments in which tones or clicks have been presented to anesthetized animals it has been the cortical response to stimulus onset that has been observed (2). The results of this study suggest that the rise-time of the stimulus is a prime-determiner of the nature of this response (6).

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6. The research reported here was carried out at Lehigh University and was supported in part by contracts and grants from the Office of Naval Research and the National Institutes of Health: Portions of the present paper were presented before the Acoustical Society of America, May, 1958.

# SENSORY FEEDBACK INFLUENCES ON MOTOR PERFORMANCE*

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The idea that various motor functions of the organism are closely linked to sensory processes is contained in the earliest sensory physiologies. In the middle ages, mental faculties were commonly located in the cerebral ventricles. Events in the outside world were considered to produce a flow of spirits through nerves to the common sensorium, located in the anterior ventricle. In the common sensorium, sensory influences were integrated and passed progressively backward through the ventricular loci of "fancy," "imagination," "thought" and "judgment." After judgment had been made, appropriate motions could be executed through the passage of spirits back along the nerves to the muscles, thus completing the events of a crude sensori-motor arc (18).

Descartes provided one of the clearest early models of the relations between sensory and motor events, antedating by centuries the precise experimental definition of neural reflexes (14). During the nineteenth century ideas about the relationships between sensory and motor events achieved a new clarity both in theory and in laboratory investigation. In the early part of the century Sir Charles Bell and François Magendie, discovered the sensory and motor functions of the spinal roots (1, 17). The idea that sensory information coming from muscles to the central nervous system plays an important role in the control of movement was clearly stated by Bell in 1826. In his paper "On the nervous circle which connects the voluntary muscles with the brain," Bell writes (2):

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"Between the brain and the muscles there is a circle of nerves; one nerve conveys the influence from the brain to the muscle, another gives the sense of the condition of the muscle to the brain. If the circle be broken by the division of the motor nerve, motion ceases; if it be broken by the division of the other nerve, there is no longer a sense of the condition of the muscle, and therefore no regulation of its activity."

The profound motor deficits in limbs made insensitive by section of their posterior spinal roots was observed in the frog and dog by Claude Bernard in 1858, and in the monkey by Sherrington and Mott in 1895 (3, 19). Sherrington and Mott reported that section of all the dorsal (sensory) roots to a monkey's limb resulted in a complete loss of voluntary movement of that limb. However, the limb could still be moved if the animal was caused to struggle, as during recovery from anesthesia. Electrical stimulation of the motor cortex, and experimentally produced epileptic attacks (intravenous absinthe) resulted in movements of the deafferented limb which could not be distinguished from movements of the normal limb.

Sensory information seems to be particularly important for normal *voluntary* movement. Non-voluntary types of movement can occur in a deafferented limb as noted by Sherrington and Mott. In this regard, it has recently been demonstrated that monkeys can be reconditioned to produce flexion avoidance responses with completely deafferented limbs (16).

Evidence for the importance of sensory information for the control of voluntary movement also comes from clinical observations such as the difficulty of the deaf in monitoring speech and the ataxia which follows lesions in dorsal roots and dorsal columns.

The fact that sensory information is vital for the initiating and control of normal voluntary actions suggests that the sensory information which is produced as a function of movement is utilized by the nervous system during the course of movement. This concept of sensory information functioning as a persistent controlling influence on motor performance fits the formal model of a servo system developed in engineering theory. In this model, the sensory information issuing from a motor performance is called "feedback." It is produced as a result of our own actions, and gives information about these actions to the nervous system; some portion of which is presumably capable of using this sensory information to control movement.

How can we distinguish what types of sensory feedback are essential for the regulation of specific motor performances? Fulton reports an experiment of Sherrington's in which one cat has all four extremities cutaneously denervated from knee and elbow distally, and another cat has dorsal roots sectioned for all four extremities (15). The first cat was able

to climb the rungs of a ladder and quietly drink a bowl of milk at the top. The second cat frequently fell while trying to climb the ladder, and actually never reached the top. The experiment is interpreted as demonstrating the essential role of proprioceptive information for the control of locomotion, and the relatively unimportant role of cutaneous information. In this experiment, the measure of motor disturbance is of course quite gross, and the perfect separation of cutaneous and proprioceptive sensory feedback influences on the motor performance is not possible, since dorsal root section cuts off the entire sensory input to the cord from the levels in question.

The sensory feedback model suggests that specific changes in motor performance should follow an alteration in the sensory feedback information being utilized to monitor that motor performance. It is the purpose of this paper to demonstrate some of the specific changes in the motor performances of human subjects which follow specific alterations in sensory feedback. Our experiments are concerned with the effects of sensory feedback alterations on performance for two voluntary motor systems: speech and keytapping.

Our studies on the effects of sensory feedback alterations on speech have all utilized a time delay in the air-conducted return of a speaker's voice to his ears. We refer to this experimental condition as delayed auditory feedback, or DAF (6). The delay in auditory feedback is achieved by permitting the record and playback heads of a magnetic tape recorder to operate simultaneously. The delay in auditory feedback is a function of the distance between the heads, and the speed with which the tape traverses this distance. When a subject speaks under delayed auditory feedback, his vocal output is picked up by a microphone; the signal proceeds to the record head of a tape recorder; it then passes on the tape to the playback head, from which it is picked up, amplified, and returned to the subject's ears via headphones.

When a delay is instituted in the auditory return of a speaker's voice to his ears, his speech is markedly disturbed (6). The sound intensity usually increases, as does the phonation time. There is a tendency to repeat sounds (5), and the normal temporal pattern of speech is sometimes completely obscured.

There is a wide range of normal variation in the amount of speech disturbance which follows delayed auditory feedback. The same delay conditions which result in barely perceptible changes in the speech of some subjects completely impede the speech of others. We measure the effect of DAF on speech by computing "correct word rate scores" (13). The sub-

ject reads passages of fixed length under synchronous and DAF conditions. The tape recordings of these passages are reviewed by scorers who count any unambiguous misarticulation as an error. The number of error words is subtracted from the total number of words in the passage to obtain the number of correct words. The ratio of correct words over the time in seconds taken to read the passage gives a correct word rate measure, which serves as a fairly sensitive index of the amount of disturbance produced.

Although the decrease in correct word rate under DAF varies greatly from subject to subject, we find that a given subject responds to DAF with the same amount of speech disturbance under test and retest. This observation can be made even when the retest follows the test by many months. It would appear that some individuals are consistently more dependent on an unaltered auditory feedback for the monitoring of their speech than others.

The amount of disturbance of speech under DAF varies as a function of the time delay of auditory feedback. In a study using 15 subjects we have found that disturbance of speech increases as delay is increased from 138 to 244 msecs. Studies by others have shown that correct word rate begins to return toward normal with delay values greater than 300 msecs. (4, 6).

Is the disturbance in speech which follows a delay in auditory feedback due to the fact that little or no air-conducted auditory information is returning to the nervous system at the normal time? Or does a delay in auditory feedback result in a disturbance of speech even if all the air-conducted sensory feedback information which normally accompanies speech is present? We can decide this question by providing simultaneous synchronous and delayed auditory feedback (12).

In Fig. 1 it will be noted that the correct word rate rises when simultaneous synchronous and delayed auditory feedback (of equal intensity) are presented to the subject's ears, but it does not reach the control value. It would thus appear that providing the speaker with all of the air-conducted auditory feedback he normally has is not adequate to nullify the tendency of a delay in auditory feedback to lower the correct word rate.

We have found that the amount of disturbance in speech under DAF varies as a function of age (11). We have studied the changes in speech produced by a 200 millisecond delay in auditory feedback in a group of 60 normal children ages 4 through 9. Analysis of tape recordings showed that the speech of the children 4-6 years of age was markedly less disturbed than was the speech of the older children, 7-9 years of age. It would

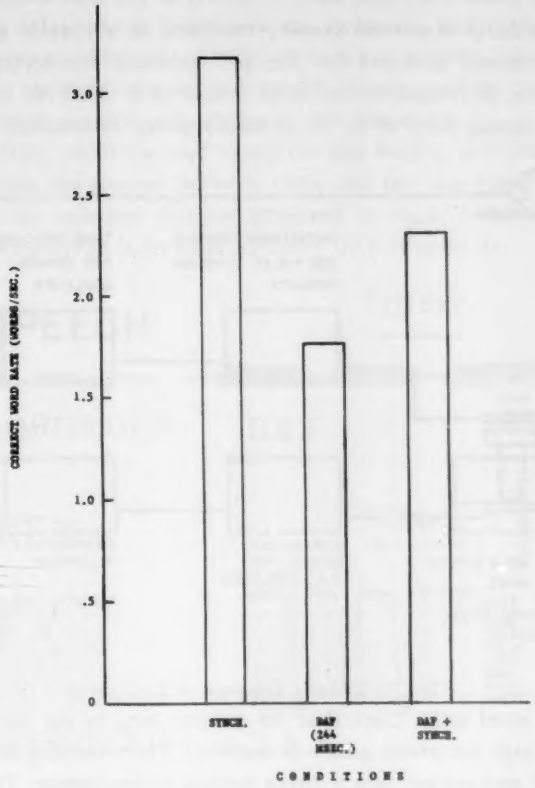


Fig. 1 Mean correct word rates under synchronous, delayed, and simultaneous synchronous and delayed auditory feedback (N=15).

appear that the dependence on an unaltered auditory feedback for the monitoring of speech increases with increasing age. This generalization must, however, be considered tentative until the study is repeated at several delay values or until our understanding of the mechanism by which delay creates a disturbance in speech is better understood.

We have also explored the question of whether stutterers respond to a delay in speech feedback in the same way as non-stutterers. To our surprise we observed marked improvement of speech under delayed auditory feedback for 10 of the 30 stutterers tested.

The difficulty of quantifying changes in speech, coupled with the fact that air-conducted auditory feedback is the only sensory feedback channel for speech conveniently altered in the laboratory, prompted us to

study the effects of altered sensory feedback on a simpler motor task. We have instrumented to record the time and amplitude characteristics of key-tapping motor performance. The subject taps on a metal rod which rests on a strip of spring steel (Fig. 2). A strain gauge is mounted on the under

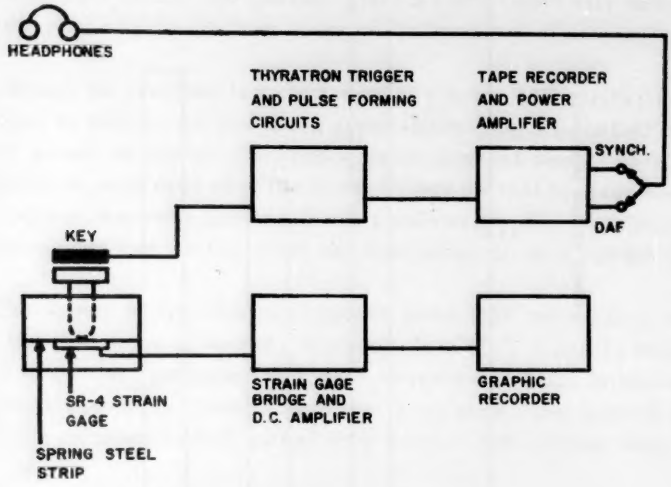


Fig. 2 Schematic Diagram of Equipment

side of the steel strip. Each time the subject taps on the key, the current passing through the strain gauge is modified. The resulting altered voltage is amplified and passed into a direct writing galvanometer. The deflection of the galvanometer pen is directly proportional to the force with which the subject taps the key.

We first investigated the effects of a delay in auditory feedback on keytapping. We were interested in finding out whether the changes in key-tapping with a delay in the auditory feedback which accompanies this type of performance would bear any resemblance to the changes we had observed in speech under DAF (7).

Each time the subject tapped on the key, he closed a circuit which resulted in the discharge of a capacitor into the amplifier of our tape recorder. The resulting click was 400 microseconds in duration and was filtered to include only frequencies from 500 to 2000 cps. By using the tape recorder in the manner described above for speech the click was passed to the subject's earphones either with or without delay. Fifteen subjects were asked to repeat the speech sound "b" as in "book" in groups of three sounds each under synchronous and DAF. The same sub-

jects later tapped on a key in groups of three taps each under synchronous and DAF. The delay time in both cases was 244 msec., and the same amount of gain was always added to the auditory feedback signals. Intensity measurements were obtained for taps and speech sounds, and the time from tap to tap and speech sound to speech sound was measured.

Under DAF, subjects tend to tap the key harder, hold down the key longer, increase the pauses between taps, and tap four times instead of three. Thus, the changes that are observed in vocal performance under DAF are also observed in keytapping under DAF (Figure 3).

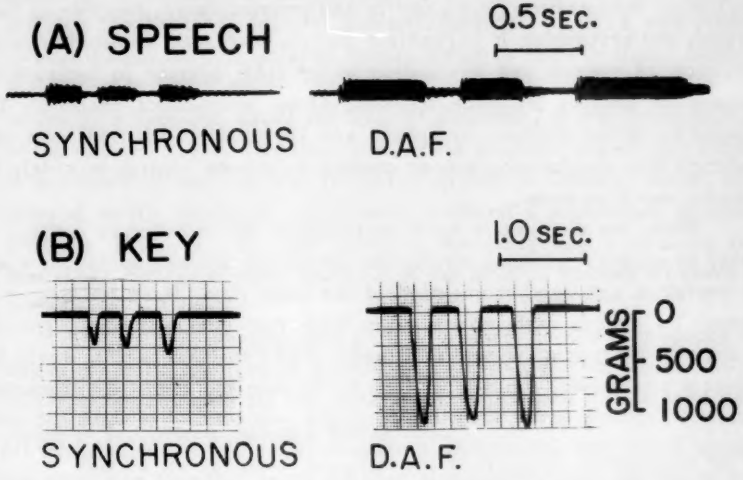


Fig. 3.

(A) Oscillograms of a group of three articulations of the speech sound "b." The height of each sound display is proportional to vocal intensity. Under delayed auditory feedback, increases occur in vocal intensity, in phonation time, and in time between sounds. Errors in number are not shown.

(B) Display of amplitude and time characteristics of a group of three taps on a key. The downward displacement from the base line is proportional to the pressure exerted on the key by the subject. Under delayed auditory feedback, increases occur in pressure, in the time the key is held down, and in the time between taps. Errors in number are not shown.

The fact that such marked changes in motor performance result from a delay in auditory feedback indicates that there may be critical time periods within which the sensory feedback accompaniments of a motor operation must be received to insure optimal motor control. Exceeding such critical time periods for auditory feedback seems to be more disorganizing

to the motor operations studied than removal of auditory feedback altogether (9). More generally, it would seem that similar temporal alterations in sensory feedback may have similar effects on widely divergent motor functions. The parallel nature of the changes in speech and keytapping following the same delay in auditory feedback is consonant with this idea

Performance under DAF probably also reflects mechanisms operating to restore control of the disordered motor function. Types of sensory feedback other than auditory, e.g., tactile and proprioceptive, function in both speech and keytapping. It is possible that the increased amplitude characteristics of speech and keytapping under DAF operate to increase the amount of sensory feedback returning along undisturbed channels. The similarity of the changes in speech and keytapping with DAF may also indicate that similar mechanisms operate to restore control in widely divergent motor systems.

While the changes in motor performance which occur as a result of delay in auditory feedback are similar for speech and keytapping, it would be useful to ask another question of the same data. Does the degree of change in speech performance under DAF correlate with the degree of change in keytapping performance under DAF? In other words, would the subjects who showed the most change in the time and amplitude characteristics of speech under DAF be the same subjects who show the most change in the time and amplitude characteristics of keytapping under DAF; and would the same relationship hold for those subjects who were minimally disturbed by DAF?

Our findings reveal that there is no significant correlation between the time and amplitude changes in speech under DAF and the time and amplitude changes in keytapping under DAF. It appears that a given subject is not equally disturbed by a temporal alteration in auditory feedback regardless of the motor performance he is monitoring. Instead, the disturbing potential of a delay in auditory feedback for a given subject seems to vary with the specific motor task being monitored. It is possible that every person learns motor skills by integrating sensory feedback information in a highly characteristic manner. The pattern of sensory feedback which is integrated in the process of learning motor skills may then determine the specific pattern of sensory feedback necessary for monitoring the motor performance in question. The disturbing potential of a given sensory feedback alteration would, therefore, be specific for each type of motor performance.

Having established that a delay in auditory feedback produces similar changes in performance of different types of motor activity, we may now ask whether delays in different types of sensory events will have a similar effect on the same motor activity. A population of fifteen subjects was trained to tap on a key in groups of three taps each at a specific rate and with a specific amount of pressure (9). Each time the subject tapped on the key, he functioned as a switch, and triggered the presentation of a sensory event, which would always occur 300 msecs. after the key had been tapped. The subject's ability to maintain the trained rate and amplitude of tapping was tested under three separate conditions of delayed sensory feedback: 1) delayed auditory feedback (a click was presented through earphones), 2) delayed visual feedback (an electronic flash tube discharged behind a plastic screen), 3) delayed tactile feedback (a dowel, moved by a solenoid, struck the subject's forearm). It was found that each of the delayed sensory feedback conditions produced significant increases in amplitude of tapping, and decreases in rate of tapping, except for the delayed tactile feedback, which only produced a significant increase in intensity of tapping. We also observed that there was a tendency to tap four times instead of three under all of the delayed sensory feedback conditions.

Our findings suggest that delayed sensory feedback produces qualitatively similar changes in performance not only across widely divergent motor tasks but also for the same motor task when the delayed sensory event is in different sensory modalities.

What is the potential significance of the type of research we have been discussing? Precise understanding of the changes in motor performance which follow specific alterations in sensory feedback may give us a diagnostic tool for the appraisal of disturbed function of neural structures which make up the different sensory feedback loops. For example, if the cerebellum does indeed play a critical role in the utilization of sensory feedback for the monitoring of voluntary movement, then patients with cerebellar disease may respond to experimental alterations in sensory feedback in a manner which is different from that of people with normal cerebellar function. We may in this way gain some useful insight into cerebellar physiology.

The fact that speech and keytapping performances are so radically altered under delayed auditory feedback permits us to use these techniques as hearing tests. A delayed click must be heard to produce changes in keytapping, and delayed auditory feedback of speech must be heard to produce changes in speech. If the delayed auditory feedback is not heard, no change in either performance will result.

In a recent study we observed that a delayed click only 10 db above the threshold of hearing produced significant disturbance in keytapping for 15 out of 20 individuals tested (10). Further studies with patients who have hearing losses are in progress in order to determine the sensitivity of this technique as a way of clinically evaluating hearing losses of varying types.

In addition to the diagnostic possibilities implicit in sensory feedback research, a number of therapeutic implications are also conceivable. Knowledge of the alterations in motor performance when sensory feedback is altered is pertinent to the question of prostheses for sensory losses (20). If a motor deficit results from a sensory lesion, such as the ataxia of dorsal column disease or the poorly monitored speech of the deaf, can we increase motor control by supplying the organism with types of sensory feedback other than those which can no longer pass to central neural structures? Characterization of the compensatory mechanisms which probably function when an experimental sensory feedback lesion is produced may also give clues pertinent to the question of sensory prosthesis. Our experimental techniques permit exploration of the value of types of sensory feedback other than those which operate normally in the control of a given type of movement. For example, can we partially correct the disturbance of keytapping which follows a delay in auditory feedback by providing a flash of light synchronized with the taps?

## SUMMARY

The present discussion has concerned the role of sensory feedback in the control of voluntary movement. Delays in auditory feedback were found to produce similar changes in speech and keytapping motor performances. These changes consisted of increases in amplitude, decreases in rate of performance, and a tendency to make repetitive errors. Similar changes were produced in keytapping by delaying different sensory events: a click, a light flash, and a tactile pulse. These findings suggest that delayed sensory feedback produces qualitatively similar changes in motor performance even when there is great variation in the motor performance under study, and in the sensory event being delayed. The potential diagnostic significance of sensory feedback research in the clinical evaluation of feedback monitoring systems as well as potential therapeutic applications were discussed.

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# HUMMING, SOUND AND SYMBOL*

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Sounds that have no dictionary meaning may nevertheless be informative under certain circumstances. For instance whistles, body slapping, clicking with the fingernails, and other human noises are used to transmit fairly complicated messages when the rules about the usage of such signals are known to both sender and receiver (16). The purpose of this brief report is to discuss the possible significance of humming and to present a number of clinical observations about this interesting form of human sound-making.

## SOME FACTS ABOUT THE HUM

The hum is a pleasant, soft, musical sound produced by singing with the mouth closed. A hum has a mellow tonal quality; it is composed of a laryngeal fundamental with few overtones, and resembles the sound made by a bass flute. As a form of pleasurable self-stimulation, humming excites the throat, mouth, and nose, setting the surrounding skin and mucous membranes into vibration. This leads to a warm, tingling feeling over the lower part of the face. Intense humming may also involve acoustic resonance of the facial sinuses and other head structures like the teeth, lips, and nose; it has a rich, cello-like quality. The loud hum which causes the teeth and bones of the jaw and throat to resonate adds a light tickle to the pleasant sensation.

The humming of animals provides us with some clues as to the function of this sound in human behavior. Purring, for example, is a hum commonly associated with cats. It is restricted almost exclusively to domestic cats and other Felidae. According to Bell, cats purr "because they have entered a certain emotional state: they are relaxed, and are without any form of apprehension, being at peace with the world around them." (2) During the cat's relaxed state, the muscles which control the vocal cords apparently slaken, and the cords move in the stream of respiratory air, producing the purr.

Some animals hum when they try to elicit attention from each other, as for example the Panama Howling Monkey; the baby makes a humming

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This paper, while not exactly in the tradition of experimental auditory research, is offered here in the hope that its many original and intriguing ideas will stimulate thought and perhaps generate testable hypotheses on the part of some of our readers.

sound when it seeks coddling from its mother (4). Apparently animal hums can also become meaningful for human listeners: it has been noted that certain creatures turn to humans for mothering and affection, particularly when a human being offers himself as a substitute source of love to the animal shortly after it has lost its parents (15). In such cases the human pseudo-parent, particularly if he or she is also lonely, may use the animal as a focus for private fantasies. Children develop fanciful ideas about the sounds of animals this way; and it is not surprising that in a child's mind the buzzing of insects, the fluttering of hummingbirds, the chirping of grasshoppers, and other nonhuman noises may come to have elaborate imaginary meanings (21).

The exact evolution of humming in the history of mankind is not known. One theory is that primitive man, like the higher apes, may have used a relatively small number of speech sounds for communication (18). According to this point of view, cries, grunts, screams, and other noises of primitive man probably sufficed for communication about shelter, food, and sex. In line with this idea, one might suppose that humming, which is a relatively easy sound to produce, also played a role in aboriginal communication. Perhaps as groups began to organize for hunting, agriculture, and other communal enterprises, man standardized his primitive noises and came to use the hum as a more specific linguistic sign. A short humming sound, the phoneme /m/ occurs in all European languages, and according to Voelker makes up about 4½ per cent of the consonants occurring in formal English speech (11).

But what about nonverbal humming? Some additional clues come from the field of musical composition: humming adds a quasi-instrumental quality to vocal music, one which many listeners find ethereal, unreal, and mysterious (10). For example in the opera Rigoletto by Verdi, wordless singing is used as a sound-effect to suggest the howling of the wind. Contemporary composers (Boulez, Nono, and others) also make extensive use of humming as a means of bringing varieties of vocal color into their instrumental works.

Another useful fact is that humming is a diagnostic sign in medicine: a hum indicates the site of certain disease processes to the alert physician. For instance, engorged blood vessels have characteristic hums due to eddies of slowed-down blood. Hyperthyroidism, splenic peritonitis, arterio-venous fistulas, and pregnancy can also be diagnosed on the basis of distinctive humming sounds (5).

## EMOTIONAL MEANINGS OF HUMMING

In the analysis of any bit of human behavior, it is well to consider independently what this behavior means in emotional terms, how it is used in action, and for what it comes to stand symbolically. Let us first consider the emotional meaning of humming since this is more difficult to put into words than are its actional or symbolic meanings. During early infancy when the human being is unable to express itself in words, humming seems to become a part of its total emotional experience of being with mother. Many steps are involved in this process: following birth, the infant and the mother are in a symbiotic relationship that resembles their physiological interdependency in the uterus. The infant instinctively tries to nurse on the mother in order to be nourished. It makes mouth movements in anxious anticipation of the feeding, vigorously sucks during food-intake, and smacks the lips afterwards while pleasantly satiated (24). Unless the mother resists this instinctive behavior, she usually enjoys feeding the infant and the associated physical intimacy. In this setting of mutual contentment humming may be heard for the first time. The mother herself may initiate the hum, as many do while feeding their children, singing lullabies, and rocking them to sleep.

It is difficult, if not impossible, for a person to remember this infantile phase of life. But occasionally during dreams, intoxication, or revery states some memories of very early childhood may come to consciousness and from these one can reconstruct the emotional meaning of humming. For example, in a study by Greenson, a patient in psychoanalysis began to experience a humming sensation in her mouth (8). Later she dreamt about a velvet cloth, and this brought to mind thoughts about delicious tactile, temperature and taste sensations localized predominantly in the mouth and hand. Following this she experienced the memory or fantasy of pleasure at the mother's breast.

Many mental traces are later superimposed on these early memories of nursery experiences: nursing is not uniformly satisfying, and particularly with clumsy, hasty or angry mothers the infant may experience oral frustrations which can be remembered in later years. Especially when the teeth erupt, the physical and psychological relationship between mother and child undergoes a change. The baby feels pain in the mouth and feeding becomes associated with new kinds of mouth movements (13). The jaws become more active, the lips are closed, and along with an increase in bodily motility, more vigorous biting and chewing occurs. The child is now capable of acting destructively; psychoanalytic studies indicate that it may develop fears of aggressive impulses, in particular a dread of biting

and hurting the mother (1). The significance of humming in such negative affect states is not yet known. But we do have some information about the way people use humming in action as a way of dealing with the outside world, which will now be considered.

## HUMMING USED AS A MASKING NOISE

In addition to its use as a stimulus for self-induced affects which has already been mentioned, humming has an important behavioral function in communication between people. It is used as a self-regulated "masking noise" to screen out sound stimuli from the external world. An acoustic explanation for this phenomenon will immediately become apparent if we remember how valuable pure tones (such as humming) are in the production of masking effects (3). When a person hums he can blot out most of the sounds of speech, as well as other noises of the environment occuring in the masked portion of the sound spectrum. For instance, a sufficiently intense hum at 500 cycles per second would mask sounds in the 1000 to 2500 cps range, which is where some of the essential cues for intelligibility of speech--for example the second formant--are found.

This may explain in part why people hum when they do not want to be disturbed by external sounds and noises. Many hum to themselves while concentrating on tasks, particularly if these involve abstract thinking or fine motor skills. Patients in psychotherapy occasionally hum in an effort to ignore what the psychiatrist has to say. Self-distraction may also be one of the mechanisms involved in the anesthetic effects of masking sound, for instance as applied in dentistry (6).

Among schizophrenic persons humming is associated with a more general withdrawal from the realities of the outside world. For example, a patient observed in the psychiatric clinic used humming to remove himself from uncomfortable environmental situations. This man had never learned to speak in articulated words. When one tried to talk with him, he made a variety of grunts and hisses, and periodically started to hum. While humming he would slip into a revery, smile inappropriately and remain out of contact with the real situation that confronted him. He picked his nose, ate the contents, engaged in small jiggling movements with arms and legs, and emitted flatus. For this very disturbed person humming was clearly part of a deeply regressive act.

Psychoneurotic patients may use humming as part of an attempt to keep troublesome fantasies out of awareness. This is particularly true if the hum is in the form of an obsessive musical theme. Sherwin reports a patient obsessed with a tune from "Lady in the Dark." The tune was used to cover up some feelings about his mother which the patient could not

consciously recognize and accept (23). In a similar case, a patient in psychoanalysis found himself obsessed with the music from an aria of Bach's St. Mathew Passion. The words of the aria, which he could not remember, had to do with murder, a subject particularly difficult for him to think about in an openly conscious manner.

Humming can also be the result of inhibition of aggressive activity directed towards the outside world. In our culture there is less objection to humming than to the sudden expulsion of air by belching or flatulence. In contrast to air expelled through the mouth, as in coughing, burping, the expiratory phase of yawning, and speech, humming produces a softer sound. Hence a youngster is less likely to be scolded for humming than for louder noises; if the humming is musical, he may even be praised. The humming child runs into little or no danger of interference with his activity from others. Yet his form of self-expression contains a particularly autistic element, for the very reason that it is not interfered with. Not subject to correction by other persons, emotions and fantasies associated with humming may remain unchecked, permitting the child to enjoy an unreal sense of power and superiority in his private world. We shall next consider some of these fantasied symbolic meanings of the human hum.

## THE SYMBOLIC MEANINGS OF HUMMING

Since we have already learned about the infantile association between the hum and blissful feelings in the mother-child setting, it is not too surprising to discover that for many persons humming and similar forms of musical behavior are symbolic substitutes for love. This was well demonstrated by the case of a depressed painter who requested psychiatric treatment at a time in his life when he had few, if any, truly affectionate relationships. He had previously sought love in casual affairs, but seldom attached himself longer than a few days to another person. This attitude resulted in considerable conflict about whether to let himself feel attached to his physician during a course of psychotherapy that might take months if not years. After a few interviews he began to experience profound anxiety when faced with the prospect of revealing his private thoughts and feelings to the psychiatrist. He dealt with this problem at first by adopting a highly intellectual approach to therapy. Being an artist, he was able to engage in pseudo-aesthetic dissections of everything he saw. He commented critically on the color patterns of paintings and furnishings in the room, disconnecting and anatomizing everything in sight. This intellectualization worked as far as aggressive and destructive impulses were concerned. But when it came to passive and erotic strivings, these were expressed musically. The patient found himself

thinking about and actually humming certain fragments of music, invariably tunes from songs or other compositions with unmistakable meaning. For instance, instead of talking of a wish for closeness and affection, he might hum Grieg's "I Love You."

Like any sound which has no generally agreed-upon definition, humming can have multiple and contradictory symbolic meanings. The dictionary mentions that humming may convey disapproval, embarrassment, and dissent. Why do so many persons consider humming sounds annoying? A possible explanation is that the unconscious connection between humming and the loss of maternal love may be recognized. Since every human being has to undergo the pain of separation from the mother, and humming may represent an attempt to recover from this, one can see that the hum could symbolize a counterfeit or dehydrated version of mother-love. Like many gestures, the hum seduces but does not satisfy; humming is like thumb-sucking without the thumb.

Seidenberg has made interesting observations on the way a child may attribute unpleasant symbolic meaning to a humming sound: a mother kept an electric egg beater running outside her child's bedroom supposedly to help him overcome his fear of noises. When the child later came to psychiatric treatment, because of extreme passivity, it was found that in his fantasies the child had managed to conceptualize his mother's vagina as a dangerous instrument with internal whirling blades (22).

Another example of the sexual symbolism of humming--in this case a mental image of musical tone--comes from Strawinsky's autobiographical accounts: One night before going to bed the composer was troubled by a certain tonal interval which kept coming to his mind. He dreamt about this: The interval "....had become an elastic substance stretching exactly between the two notes I had composed, but underneath these notes at either end was an egg, a large testicular egg. The eggs were gelatinous to the touch (I touched them) and warm, and they were protected by nests. I woke up knowing that my interval was right" (25).

Since in humming air must pass through the nose, it is not surprising that the hum so often has a symbolic meaning connected with the erotic. In fantasy, the nose frequently represents a bisexual organ (20). In analogy to the penis it protrudes from the body, emits substances, and is covered with skin; and like the vagina the nose is hollow, permits insertion, and is lined with mucosa. Like nose-picking, humming is a displaced form of masturbation among certain emotionally disturbed persons.

## THE VERBAL MEANINGS OF HUMMING

There are two forms of humming in verbal discourse: the word *hm* and the phoneme /m/. The word *hm*, according to Jaffe, constitutes a significant portion of the verbal responses of psychiatrists (12). Since its meaning is not defined in the dictionary, this word is open to a number of possible interpretations.

*Hm* tends to be understood as a question when it has an upward inflection that resembles the sounds associated with doubt or pleading (19). Two staccato *hm's* uttered in rapid succession with a rising inflection generally suggests affirmation (9). An up and then downwards inflection of *hm-hm* suggests a number of feeling states such as surprise, amazement or interest. Undulating *hm's* suggest unrest, anguish, uncertainty, or alarm, probably because of the resemblance to the sound of a whine or siren.

For the phoneme /m/ we must again turn to studies of language development. The earliest communicative signals emitted by humans are mainly cries composed of sounds resembling the vowels [a], [*a*], [*e*], [ɛ], and the consonants [h], and [ʔ]. According to Irwin [m] constitutes less than 1 per cent of all the consonant sounds produced by the child during the first month of life (11). This low incidence easily leads one to underestimate the importance of the hum-like sound during infancy.

Lewis linked /m/ specifically with the sucking mouth movements of newborn infants waiting to be fed (14) . He observed that "if the child phonates while making these anticipatory sucking movements, the sounds produced will approximate to the labial and dental consonants. If, further, he is in a state of discomfort, such as hunger, and phonates nasally--as we have seen he does--then the consonants produced will inevitably be *m* or *n*." By the age of six months, when teeth have started to appear, [m] makes up 3 per cent of the baby's consonants, rises to 9 per cent shortly after the first birthday, and stays close to 8 per cent for the next year and a half.

To become linguistically meaningful, the child's spontaneous utterance of /m/ must be reinforced by parents or other speaking adults. Such reinforcement can occur in a variety of ways. What usually happens is that the baby's random mouth noises are mistaken for formed speech elements. Parents may be delighted to find that their baby can already make recognizable sounds. In their eagerness to communicate, babies may repeat the mouth sounds which please their parents. But as a phoneme, /m/ can only function in conjunction with other speech sound; in isolation it has no verbal meaning. To what extent its early association with oral fac-

tors causes the /m/ to impart a maternal feeling to words which contain this phoneme is not yet known. But note the high incidence of /m/ in words signifying mother (mom, mummy, mutti, mere, madre, etc.), and at the beginning of female names (Mary, Martha, Margaret, etc.). This may be one way in which the emotional hum of children survives as a depersonalized linguistic sign in adult communication (7).

## SUMMARY

Humming is a sound produced by singing with the mouth closed. It may be used to express pleasurable emotions related to mother-love and satiation. Humming can also be involved in aggressive and masturbatory behavior. As a masking noise, humming helps certain people to withdraw from external stimuli during states of revery, intellectual work, and obsessional preoccupation. In verbal discourse, humming occurs as the word *hm*, which may signify assent, negation and other possible meanings. The phoneme /m/ may provide words in which it appears with an emotional flavor that recalls the primal mother-child relationship from which humming sounds originate.

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# RELATIONSHIPS OF EDR AND EEG ALPHA RHYTHM TO PATHOLOGICAL ANXIETY

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*This research was carried out under the auspices of the Veterans Administration.*

Electrodermal audiometry is recognized today as one of the more successful techniques available for assessing the hearing acuity of persons whose voluntary audiometric thresholds are unreliable. Notwithstanding the success of this procedure, its application to some reported cases has been no more successful than routine audiometry in the determination of hearing acuity (4, 5, 6).

Because of this problem, attempts have been made to identify some of the major variables that may contribute to differences among individuals with respect to conditioned electrodermal response (EDR). One variable which has received attention is the presence of neuro-psychiatric disorder. More specifically, it has been observed by some investigators that patients whose diagnoses include neuro-psychiatric abnormalities often yield equivocal electrodermal audiometric results (6, 8). Even when the diagnosis is obscure, it has been found that subjects who exhibit evidence of "non-organic" hearing problems are difficult to condition to auditory stimuli (5).

In contrast to the above findings, other researchers have found evidence which suggests that a neuro-psychiatric syndrome of pathological anxiety may actually enhance electrodermal responses. Welch and Kubis (9) state that psychiatric patients with anxiety required fewer conditioning trials than did normal college students in order to become conditioned to visual stimuli. It was also found that the extinction of the EDR was less rapid in the pathologically apprehensive subjects than in the normal subjects (10).

A somewhat different approach to the problem was taken by Charan and Goldstein (1), who suggest that individual differences in conditioned electrodermal response are as much dependent on "some basic psychophysiological trait" as on specific pathology. They found that this "psychophysiological trait" seemed to be reflected by the presence or absence of EEG alpha rhythm in subjects who were presumably normal psychiatrically. It was observed that normal-hearing male adults whose EEG tracings were characterized by a predominance of alpha rhythm gave fewer electrodermal responses to pure tone stimuli than did those subjects who exhibited a low percentage of alpha rhythm.

Although the literature presents a relatively confusing picture of the effect of neuro-psychiatric disorders on the EDR, the basic procedure used by Charan and Goldstein (1) seems to offer a fruitful approach to the problem. More specifically, it is known that alpha rhythm most often accompanies a psychological state of alertness and is commonly obliterated from the EEG record in states of extreme relaxation and sleep. Therefore, it might be reasonable to expect that subjects who are pathologically apprehensive would exhibit more alpha rhythm in their EEG patterns when compared with psychiatrically normal subjects. It might also be expected that the former type of subject, by virtue of his anxiety state would attain a conditioned EDR more rapidly and extinguish the response more slowly than would the latter type of individual.

The present study was designed to investigate these aspects of the electrodermal response in hard-of-hearing subjects with pathological anxiety.

The rapidity of EDR conditioning, as well as the EDR extinction rate was related to the presence of prominent EEG alpha rhythm in these individuals. A group of psychiatrically normal hard-of-hearing subjects was similarly studied for purpose of comparison.

## SUBJECTS

Sixteen armed forces veterans, between the ages of 24 and 46, were selected as subjects for this study. Half of this number comprised the control group, while the other half comprised the experimental group. All subjects were required to have an average hearing loss (500-2000 cps) by air conduction of 30-60 db (re 0 db hearing level) in the better ear. An additional requisite to being selected as an experimental subject was a medical diagnosis of psychiatric pathology that included a strong anxiety component. A negative psychiatric finding placed a subject in the control group.

## EQUIPMENT

The present study was conducted in the Audiology Clinic and the Department of Electroencephalography of the New York Regional Office, Veterans Administration.

The equipment used for electrodermal audiometry was contained in a two-room, acoustically-treated suite. A pure tone audiometer (Beltone, Model 15-A) was located in the control room. The audiometer was triggered by a psychogalvanometer (Grason-Stadler, Model E664) which controlled the presentation of tone and shock as well as providing a record of changes in skin resistance during the administration of electrodermal audiometry. The test chamber contained a chair for the subject, an earphone headset

(Telephonic TDH-39, 10 ohm) mounted in MX41/AR cushions, and the shock and recording electrodes from the terminals of the psychogalvanometer. Both the shock and recording electrodes were 4 mm diameter zinc-sulphate kaolin paste.

Electroencephalography was conducted with an eight-channel electroencephalograph (Grass, Model III-A), which was placed in the control room of a two-room suite. The subject's room was darkened and contained a couch and the terminal electrodes from the electroencephalograph. These electrodes were surface-type silver discs approximately eight millimeters in diameter. Plastic-covered number 35 wire with silver-plated brass tips was used for the leads between the electrodes and the electroencephalograph. Bentonite paste served as both an electrolyte and an adhesive.

## ELECTRODERMAL AUDIOMETRY

Although each subject's electrodermal audiometric thresholds were obtained in a subsequent test session, no attempt was made to establish them during the procedure of the present study. Therefore, thresholds will not be considered in the following discussion.

*Subject Preparation.* During electrodermal audiometry subjects sat in an airchair with shock electrodes taped to the tips of the index and and third fingers of the right hand. Recording electrodes were fixed in the same manner to the tips of the second and fourth fingers of the left hand. The subject was then informed that he would hear a number of tones and would feel occasional electric shocks at his fingertips. He was cautioned against excessive movement. The earphones were then adjusted in place for testing.

*Stimuli.* A three-second duration 1000 cps tone was used as the conditioned stimulus. It was presented monaurally to the right ear 30 db above the subject's predetermined voluntary threshold at 20 to 40 second intervals.

Electric shock was the unconditioned stimulus. It was presented .5 second after the onset of the tone and lasted for .3 second. The strength of the initial shock was approximately 2.0 milliamperes. Succeeding presentations were fixed at approximately 2.5 milliamperes.

*EDR Criteria.* A judgment was made as to whether or not an EDR had been evoked after the presentation of each stimulus. These decisions were based on the excursions of the psychogalvanometer's recording stylus. An EDR was judged to be present when a stylus deflection following a stimulus:

1. was at least 10 millimeters greater than any deflection 20 millimeters before and after it.
2. dropped at a rate of at least 10 millimeters per second.
3. occurred between one and 2.5 seconds after the onset of the stimulus.

*Testing.* The conditioning series was initiated by presenting three tone-shock combinations. These were followed by three tones without shock. When each tone of the latter series evoked an EDR the subject was considered conditioned and additional tones were presented until extinction occurred. If, however, three consecutive EDR's were not obtained, the sequence of three tone-shock combinations and three tones without shock was repeated until the subject became conditioned. Additional tones without shock were then introduced until extinction of the EDR occurred. If a subject received fifteen presentations of tone and shock without becoming conditioned, testing was terminated.

The time required for electrodermal conditioning and testing ranged between 10 and 25 minutes.

## ELECTROENCEPHALOGRAPHY

*Subject Preparation.* The subject was placed on a couch in a darkened room and the EEG electrodes were fixed to the scalp bilaterally in frontal, parietal, temporal and occipital positions (3). An additional electrode was placed on each ear to serve as an indifferent reference for monopolar recording. The subject was informed that he would receive no shock during this procedure and was instructed to relax and remain relatively immobile.

*Calibration.* The electroencephalograph was calibrated so that a pen deflection of seven millimeters represented a 50 microvolt change in electrical potential.

*Testing.* A routine electroencephalogram was recorded for each subject. Both monopolar and bipolar tracings were done. Although responses under hyperventilation and auditory stimulation were obtained for clinical purposes, these portions of the electroencephalogram were not directly pertinent to the present study and were not considered in computing the percentage of alpha rhythm in a subject's record.

As is often the case in EEG testing, some subjects fell into a light sleep during part of the test session. This fact was ascertained by the identification of "sleep patterns" in the EEG tracing. Since alpha rhythm typically is depressed or absent during sleep (3), and our study was concerned with alpha activity, only the waking portion of the tracing was used in the analysis of the data.

Electroencephalography was completed in a single test session lasting approximately fifteen minutes.

*Treatment of the Data.* Each subject's EEG pattern was relegated to either a high-alpha or low-alpha group. No definitive standards exist which dichotomize alpha rhythms into two categories on the basis of amplitude. Therefore, for purposes of comparing results with those of earlier work, the criteria used by Charan and Goldstein (1) were adopted. Specifically, the high-alpha group was characterized by waves which occurred more than 50 percent of the time, in which the maximum amplitudes exceeded 50 millivolts and the frequency was 9-11 per second. All other records were placed in the low-alpha group. The clinician who categorized the EEG tracings had no knowledge of either the psychiatric diagnosis or the EDR results for any case.

In analyzing the data, the following comparisons were made between results obtained from the experimental and control groups:

1. The number of cases that fell into the high-alpha and low-alpha categories.
2. The mean number of conditioning sequences required to obtain three consecutive EDR's to sound.*
3. The number of extinction trials required to obliterate the EDR.

## RESULTS

*Alpha Categories.* The number of experimental and control subjects who fell into the high-alpha and low-alpha classifications is shown in Table 1. It can be seen that a relatively sharp dichotomy emerged in that all but one member of the experimental group fell into the low-alpha category, while no control subjects were so placed.

*Ease of Conditioning.* The mean number of sequences necessary to condition each group is reported in Table 2. It should be noted that in this table, as well as in Table 3, the experimental group is reduced to seven cases. This reduction was due to the fact that one experimental subject could not be conditioned after five sequences (15 conditioning trials). Interestingly, this subject was the single experimental case that fell in the high-alpha category. Since this subject presented a totally different picture than did his group members, his data was given further inspection and will be discussed separately. The remaining members of the experi-

**It will be recalled that three conditioning trials were always presented before each assessment of criterion conditioning. Each three-trial series constituted one sequence in the analysis.*

Table 1. Number of anxiety and control subjects who exhibited high-alpha and low-alpha EEG tracings.

| | Anxiety Group (N = 8) | Control Group (N = 8) |
|---|---|---|
| High-alpha | 1 | 8 |
| Low-alpha | 7 | 0 |

Table 2. Means and standard deviations of sequence (three tone-shock trials to each sequence) required to establish conditioning in the anxiety and control groups.

| | Anxiety Group (N = 7) | Control Group (N = 8) |
|---|---|---|
| Mean | 1.75 | 1.50 |
| S.D. | .50 | .75 |

Table 3. Means and standard deviations of tone presentations necessary to extinguish the EDR in the anxiety and control groups.

| | Anxiety Group (N = 7) | Control Group (N = 8) |
|---|---|---|
| Mean | 25.7 | 16.4 |
| S.D. | 5.5 | 4.2 |

mental group required essentially the same average number of sequences as did the control subjects in order to become conditioned. The mean number of necessary sequences was 1.75 and 1.5 for the experimental and control groups, respectively. Inasmuch as conditioning could have taken place at any time during the three tone-shock presentations of a sequence, the present assessment is a relatively gross one.

*Extinction Rate.* An inter-group comparison of the mean number of of tone presentations that was necessary to extinguish the EDR is shown in Table 3. It can be seen that the non-organic group required an average of 25.7 tone presentations before the EDR was extinguished. By contrast, the EDR's from the control group were unrecognizable after a mean of only 16.4 trials. Stated differently, the cases with pathological anxiety maintained conditioned electrodermal response to sound through an average of approximately ten more trials than did the psychiatrically normal subjects.

In order to test the statistical significance of this difference in extinction rate, the Mann-Whitney U test was applied to the data. The results of this analysis revealed the inter-group difference to be significant beyond the five per cent confidence point.

## COMMENT

Other studies (1, 2) have reported that nearly 60 percent of normal adults exhibit EEG patterns with alpha rhythm present more than 50 percent of the time. If the criteria for alpha rhythm of 50 millivolt, 9-11 cycle waves is used, the findings of the present study suggest that such may not be the case uniformly among hard-of-hearing male adults. The fact that the psychiatrically normal subjects exhibited high-alpha EEG patterns is unexplained in the light of the existing literature. Whether hearing loss, per se, its specific etiology or some other factor is responsible for this phenomenon remains obscure.

Regardless of the underlying mechanisms which govern this behavior, the fact remains that the cases with pathological anxiety were sharply contrasted to control subjects by their relative lack of alpha rhythm. In attempting to explain this finding, one can speculate that a concurrent effect of anxiety is a chronic "alertness" which might suppress alpha rhythm. If such is the case, and it is assumed that electrodermal responses are facilitated by an increase in anxiety (7), it would not be unreasonable to expect that an unduly apprehensive individual, after having been conditioned with a noxious stimulus, might remain in a state of "response readiness" for a longer period than would a psychiatrically normal person.

To the extent that extinction of the EDR is an index of the perserverance of "response readiness", the findings of the present study lend support to this view and are in essential agreement with those of Welch and Kubis (10). Since adaptation trials preliminary to conditioning were not used in the present study, no distinction can be drawn between the extinction of conditioned and unconditioned responses.

Following the above line of reasoning, it might also be expected that subjects in a chronic state of "response readiness" would condition more readily than would psychiatrically normal individuals (9). That such an effect was not found may have been due to the relative grossness of the experimental procedure. The ease of conditioning apprehensive subjects should be investigated further, using the number of individual conditioning trials as a criterion measure.

The results of the psychiatric examination were carefully inspected in an attempt to find an explanation of the data obtained from the single non-organic subject who fell into the high-alpha group and could not be conditioned. It was found that although a strong anxiety component existed in this individual, it was present in a basically schizoid personality. No other subject was so diagnosed. Whether or not a relationship exists between presence of high-alpha activity, ease of conditioning and schizoid personality remains undetermined. It may be that this and other psychiatric etiologies are related quite differently to EEG and EDR activity than is anxiety.

The results of the present study suggest the following conclusions:

1. Hard-of-hearing male adults with pathological anxiety exhibit relatively little EEG alpha rhythm, as contrasted to psychiatrically normal male adults with hearing loss whose EEG's are strongly characterized by the presence of alpha rhythm.
2. The conditioned electrodermal response to sound seems to be somewhat more resistant to extinction in hard-of-hearing male adults with pathological anxiety than in those who have no psychiatric disorder.

## SUMMARY

Sixteen hard-of-hearing armed forces veterans, half of which were chosen on the basis of a diagnosis of pathological anxiety, were divided into two groups according to the presence of EEG alpha activity. Determinations were made regarding the ease of conditioning electrodermal responses as well as the extinction rate of these responses. It was found that the apprehensive subjects exhibited relatively little EEG alpha rhythm while the EEG patterns of the psychiatrically normal subjects clearly showed a preponderance of high-alpha activity. No difference was ob-

served in the ease of conditioning the two kinds of subject. This finding may be due to the grossness of the criterion measure employed in the present study. The EDR was more resistant to extinction in the subjects with pathological anxiety than in the psychiatrically normal subjects.

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# TTS FOLLOWING PROLONGED EXPOSURE TO ACOUSTIC REFLEX ELICITING STIMULI

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## INTRODUCTION

Recently considerable research attention has been devoted to acoustic reflex (AR) action (1, 2, 3, 4, 5, 7, 8). Reflex action has been shown to provide reasonably good protection against trauma from impulse noise for the human ear (1, 2). Upon cursory examination, it would appear that fatigability characteristics of the reflex would serve to limit its usefulness to protection from intermittent stimuli. However, several sources indicate that AR action can be prolonged. Much of this evidence is summarized and presented in a monograph by Wersäll (8).

The conditions where AR activation was prolonged were those in which continued stimulation of the reflex involved successive short term presentations of stimuli varying considerably in frequency. Lüscher (6), for example, found that after AR fatigue had been induced by a 6889 cps tone reflex contraction of unfatigued magnitude reappeared immediately following stimulation by a tone of 2734 cps, and after fatigue induced by a 5161 cps tone, a "new" contraction followed 4096 stimulation. Others (4, 7) have also reported that the reflex can apparently be restored to full strength, or prolonged in contraction, by appropriate manipulation of the reflex activating stimuli.

Consideration of the above findings indicates that it might be possible to provide AR protection for continuous as well as intermittent sound by proper selection and programming of the AR activating stimuli. The present experiment is an investigation of this possibility.

## METHOD, APPARATUS, AND SUBJECTS

A block diagram of the apparatus used in this investigation is given in Figure 1 below.

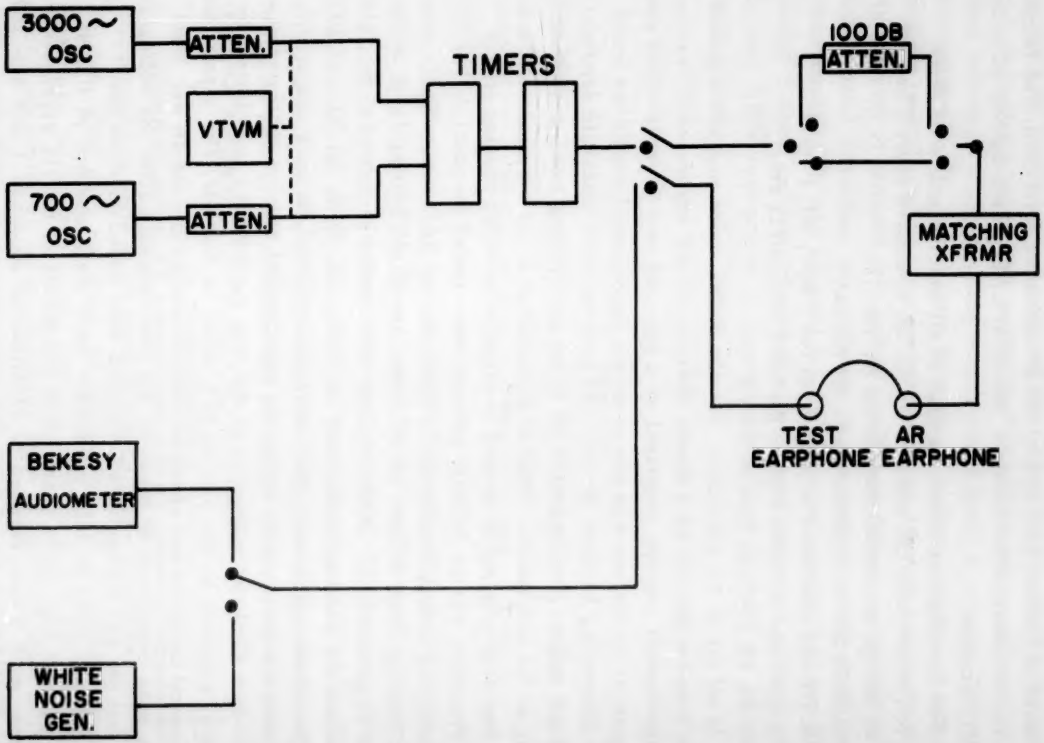


FIG. 1 BLOCK DIAGRAM OF THE APPARATUS

The AR eliciting stimulus was presented in one ear (hereafter referred to as the AR ear) while simultaneously in the other ear (referred to as the test ear) the fatiguing sound was administered. The AR activating stimuli were tones of 700 and 3000 cps at 100 db sensation level (SL). The fatiguing stimulus was a white noise at 120 db SPL. Exposure time in all cases was 12.5 minutes.

The investigation covered a total of six experimental conditions:

1. 700 *and* 3000 cps tones in the AR ear *alternated every 5 sec.*
2. 700 cps on *continuously* in the AR ear.
3. 3000 cps on *continuously* in the AR ear.
4. 700 cps alternated in the AR ear (on 5 sec., off .1 sec.)
5. 3000 cps alternated in the AR (on 5 sec., off .1 sec.)
6. *No* AR eliciting tone in the AR ear.

In all six of the conditions, the 120 db SPL noise was administered to the test ear for the 12.5 minute duration of the experimental session. An experimental session consisted of a pre- and post-exposure 4000 cps audiogram of the test ear with one of the six experimental conditions listed above intervening between the pre- and post-exposure threshold determination. Each subject participated in all of the experimental conditions, thereby serving as his own control. Order of presentation of the experimental conditions was counterbalanced in order to minimize possible training effects.

Procedure was as follows: subjects were tested for possible hearing loss using the Grason-Stadler model E800 Bekesy Audiometer. Those with normal hearing (here defined as not more than 15 db hearing level at the octave frequencies 125 - 8000 cps) then were tested to determine the voltage across the earphones necessary to obtain 100 db SL for 700 and 3000 cps. Once these preliminary tasks were accomplished for each subject (S), experimental sessions were begun. An experimental session consisted of a pre-exposure 4000 cps audiogram of the test ear followed immediately by 12.5 min. exposure to the 120 db SPL noise in that ear. The appropriate experimental condition was simultaneously channeled into the AR ear. Immediately upon completion of exposure the post-exposure 4000 cps audiogram of the test ear was accomplished. Subjects were tested once per day.

Subjects used in this experiment were staff members of USAMRL ranging in age from 19-39 years. Upon completion of the six experimental sessions, each S was exposed to experimental condition 1 and pre- and post-exposure 4000 cps thresholds were determined in the *AR* ear in order to assess changes in acuity in that ear due to exposure to the eliciting stimuli.

## RESULTS

Raw data for this experiment were the threshold shifts at 4000 cps obtained by comparing the pre- and post-exposure thresholds. We assume that prolongation of the AR contraction by any of the experimental conditions utilizing various eliciting stimuli would result in smaller TTS (temporary threshold shift, a temporary decrease in auditory acuity) as compared with the control condition (number six) where no AR stimulus was provided. An analysis of variance revealed no significant differences among the five experimental conditions as compared to the sixth (control) condition. In other words, TTS was as great for the situations provided in condition 1 through 5 where various "eliciting" stimuli were presented in hopes of prolonging reflex contraction as it was in condition 6 where no AR stimuli were presented.

Table 1 shows the mean TTS in the test ear for each of the 6 experimental conditions.

TABLE 1

| Conditions | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Mean TTS (in db) | 16.1 | 16.2 | 13.4 | 16.4 | 14.7 | 17.9 |

Testing in the AR ear immediately after exposure to condition 1 resulted in a mean TTS in that ear of 22.7 db, somewhat greater than that occasioned by exposure to the "fatiguing" sound. In this case, then, the stimuli presented to protect the subject from fatigue actually produced more TTS than did the 120 db SPL noise from which he was to be protected. Obviously then, reflex action in this particular instance was not prolonged, or the ear sustained a loss in spite of reflex action.

## DISCUSSION

Efforts to prolong AR contractions in this experiment were apparently unsuccessful in spite of evidence in the literature suggesting that it was feasible. This does not mean, of course, that AR activation cannot be maintained, merely that in this specific instance it was not. The experimental procedures of the present study show at least one clear difference from those where reflex activation was maintained. Presentation of the fatiguing sound in the test ear was simultaneous with presentation of the eliciting tone in the reflex ear. Perhaps in the absence of the fatiguing

sound reflex contraction would have continued, but a limitation of this nature would severely restrict practical application of this phenomenon. It is also possible that some other type of stimulus or eliciting signal could have maintained reflex contraction. At least three workers in AR research have separately indicated reflex contractions are not well maintained when pure tones are used as stimuli.* Whether or not *any* stimulus can maintain contraction in the ipsilateral ear when the contralateral ear is simultaneously exposed to a high level noise is problematical and, indeed, unanswerable on the basis of evidence now available.

Future development of AR protective devices should be guided by consideration of the TTS likely to be produced by the eliciting stimulus. This would be a limiting factor in protecting against continuous noise by use of the AR technique, assuming other difficulties could be overcome.

Apparently further research is indicated to determine optimum types and amplitudes of sound for AR elicitation as well as proper methods, if any, of programming stimulation in order to maintain contraction. Also, perhaps more information on stimulation necessary to fatigue reflex activity as well as data on recovery time would be extremely useful.

*W. Dixon Ward, M. Mendelson, and F. Blair Simmons. Personal communication.

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# ESTIMATING THE RELIABILITY OF AUDITORY THRESHOLD MEASUREMENTS

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The recent literature dealing with the reliability of audiometric measurements reveals that a number of different concepts of reliability have been used to express the agreement, or lack of agreement, found between successive testings of auditory sensitivity. The lack of uniformity in dealing with this common problem has made it difficult to evaluate the findings of different investigators. This paper will 1) review some of the more widely used concepts of reliability as they apply to audiometry, 2) evaluate the implications of each for audiometry, and 3) suggest a method for quantifying the reliability of audiometric data. An illustration of the suggested method will be made using auditory threshold data obtained on nine successive occasions under four different testing conditions.

## THE NATURE OF AUDIOMETRIC RELIABILITY

The problem of reliability is essentially the problem of error of measurement. Specifically, it is the question of variable error - - - error which is either positive or negative and of fluctuating magnitude. Reliability implies, therefore, consistency of measurement of the auditory threshold under different conditions.[1]

The reliability of audiograms is a problem of real concern to the audiologist: when confronted with a change in the audiogram of a given person, it is necessary to know whether that change reflects error of measurement or a shift in the hearing sensitivity for that person. Resolution of this problem is not simple and involves the consideration of an impressive number of variables.

### *Sources of Error Variance in Audiometry*

A catalogue of the major factors that can contribute to the variability of audiograms will illustrate some of the many problems involved in obtaining a reliable measure of hearing sensitivity. The following list is not necessarily exhaustive, but probably contains the majority

[1] *The conditions under consideration here are those typically encountered in clinical audiometry, as defined by Hirsh (8, p. 89), as opposed to the more restrictive conditions encountered in experimental audiometry.*

of significant factors. The variables, for the sake of convenience, have been grouped under four categories: physical, physiological, psychological, and methodological.

A) *Physical Variables*

1) Stimulus conditions - includes type of test tone, i.e., pulsed or continuous, duty cycle of pulsed tone, frequency, type of earphones and fit, pressure exerted by headband, etc .
2) Ambient noise conditions
3) Equipment variables - amount of frequency drift, accuracy of attenuator steps, type of ear cushi ons, hum, noise, and distortion in the stimulus tone, etc.

B) *Physiological Variables*

1) Volume and shape of auditory meatus
2) Age and sex
3) Pathology of the auditory apparatus
4) General health of the subject
5) Auditory fatigue
6) Shifts of the "true" auditory threshold

C) *Psychological Variables*

1) Motivation of subject
   *a) Momentary fluctuations of attention*
   *b) Attitude toward the test situation*
   *c) Personality attributes*
2) Intellectual factors
   *a) Comprehension of instructions*
   *b) Practice effects*
   *c) Test taking experience*
3) Response conditions
   *a) Type of response required of subject, i.e., button pressing, finger raising, verbal response, etc.*
   *b) Variations in the personal criterion of what constitutes a stimulus event (between subjects and within the same subject from occasion to occasion.)*
   *c) Idiosyncrasies of the total response system*

D) *Methodological Variables*

1) Psychophysical method including variations of:
   *a) Method of limits*
   *b) Method of adjustment*
   *c) Constant methods*
2) Time interval between successive tests

Failure to control or make allowance for any one or combination of these variables can lead to spurious threshold measurements. Some variables are more important than others, but in general the more rigidly the testing situation is controlled, the more reliable and valid the measurements are likely to be .

In clinical audiometry it is rarely possible to impose experimental controls to the same extent as in the laboratory. Clinical audiograms would not, therefore, be expected to be as free from error as laboratory measurements. The difference in reliability between clinical and laboratory audiograms is reflected by studies reported in the literature. Harris and Meyers (7) reported on the basis of a carefully controlled laboratory study that the standard deviations of ten threshold crossings (1 db steps) for their subjects ranged from about one to three db depending on the frequency tested. Gardner (4), using the procedures of clinical audiometry, found that the standard deviations of the difference between repeat threshold measures varied from 2.4 to 4.2 db. Samples of successive audiograms collected from industrial sources by the Subcommittee on Noise[2] showed standard deviations of repeat audiograms that ranged up to 30 db for some individuals depending on the tested frequency.

Each of the studies cited represents audiometric situations in which varying degrees of experimental control were imposed. It is apparent from these studies and others, that the quality of audiograms is directly related to the way in which they were obtained.

## METHODS FOR EVALUATING RELIABILITY

The traditional methods for evaluating reliability are basically similar, although for convenience they can be grouped into two types; those which assess the *agreement* between two or more measures of the same event, and those which reflect *disagreement* between measures of the event. The primary method stressing agreement between measures involves the correlation of scores from a first and second test. The methods stressing disagreement involve measures of variability such as the standard deviation or average deviation.

The similarity between correlational analysis and variability analysis methods is often overlooked. The correlation coefficient under some conditions is interpretable in terms of variability measures. It is known, for example, that the correlation (reliability) coefficient is equal to the ratio of the predicted variance to the total variance for a given set of scores. This same relationship can also be expressed as the quantity one minus the ratio of error variance to the total variance.

[2] *Unpublished data.*

These relationships point out the major problem in specifying the reliability of a set of scores; the problem is that of quantifying the error variance of two or more sets of test scores so that it is distinguishable from the true variance.

The majority of reliability investigations reported in the literature have been laboratory studies involving relatively short time series such as those reported by Harris and Meyers (7), Ward, (11) and Corso and Cohen (3). These studies contribute to the general understanding of audiometric reliability in two ways, first, they demonstrate the maximum reliability that can be achieved under a highly controlled set of conditions; and second, they serve as proving grounds for different methods of quantifying errors of measurement. Ward, for example, derived a special case of the standard deviation for the measurement of individual variability where only two repeat measures are available. Harris and Meyers used the traditional standard deviation applied to the differences between two sets of audiometric measures, and Corso and Cohen used a variation of the intraclass correlation coefficient to evaluate the reliability of repeat audiograms.

As the time interval between repeat measures becomes longer it is possible for a multitude of factors to operate which would not be present in a short measurement series. From the point of view of clinical and industrial audiometry, it is the changes that take place in hearing sensitivity over the longer time intervals that are of greatest interest. To date, little research has been done involving the longer time spans, say from month-to-month or from year-to-year.

### *The Standard Deviation*

This has been the statistic most commonly used to describe the reliability of audiograms. In some instances it has been derived from the distributions of difference scores found between successive testings; in other instances, the standard deviation has been derived from the distribution of successive test scores for an individual where a relatively large number of repeat tests were available.

When the standard deviation is computed for the distribution of difference scores between a first and second test, an estimate of error variance is obtained which is satisfactory for most purposes. However, this estimate of error is subject to certain limitations. A proper estimate of error variance should make allowance for the variance attributable to conditions known to produce changes in the auditory threshold during the interval between tests. Such conditions would include noise exposure, the effects of aging, learning, pathology of the ear, and the like.

The standard deviation of difference scores does not differentiate between such systematic sources of variance and error of measurement. Consequently the standard deviation may produce an inflated estimate of error variance.

The standard deviation applied to a distribution of threshold measurements for an individual yields a good estimate of the variability of the responses for that individual. This information can be of use in certain types of experiments where one is interested in the absolute amount of variation shown by a given individual over a number of tests. However, the standard deviation used in this way is subject to the same limitations as it is when applied to difference scores, that is, it does not distinguish error from systematic variance. Secondly, the standard deviation applied to successive measurements yields information for only a single individual; it has no generality because of the marked individual differences that occur in the variability of thresholds found on successive occasions.

### *The Correlation Coefficient*

In its various forms, the correlation coefficient has been widely used by psychological and performance test constructors as a measure of reliability, but only infrequently as a measure of audiometric reliability. The reliability (correlation) coefficient has one advantage that the standard deviation does not have; it takes the form of an index number that varies between -1.00 and +1.00. Because of this, and because its computation involves a transformation of raw scores to standard score form, the correlation coefficient is easy to interpret and is independent of the unit of measurement used. The standard deviation, on the other hand, can take any positive value which depends, in part, upon the discrimination properties of the original measurement units.

In spite of the simplicity of the correlation coefficient as a measure of reliability, it has never enjoyed much popularity in auditory research. Possibly it is because reliability estimates obtained from correlation coefficients have appeared to be at variance with estimates produced by other statistical methods. It is known, however, that the magnitude of the correlation coefficient depends in part on the dispersion of scores in the tested sample[3]. At the lower frequencies, e g., 125, 250, and 500 cps, the dispersions of individual threshold scores about the mean auditory threshold in unselected samples is relatively small

[3] *It is well established that restriction of range reduces the magnitude of the correlation coefficient (5, p. 348).*

compared to the dispersion at the higher frequencies. While several short term laboratory studies showed that the variability of individual threshold measurements is approximately equal for all test frequencies, reliability estimates (Pearson product-moment correlations) from industrial samples[4] indicated that the lower test frequencies were less reliably measured than the higher test frequencies. The reason for the discrepancy probably lies in the different testing methods used. Because the threshold scores of most samples tend to be closer together at the low end of the auditory spectrum than at the high end, the 5 db step interval commonly used in clinical audiometry does not discriminate between individuals equally well at all points along the auditory spectrum. It is this differential discriminability of 5 db step audiometry as a function of frequency which is indirectly reflected in the correlation coefficient. Even though laboratory investigations have indicated that fluctuation of the auditory threshold is fairly uniform at all frequencies, the reliability of 5 db step audiometry is not equal at all frequencies.

A problem that is strictly inherent in the Pearson correlation coefficient itself is that its standard error is so large that it is not practical for use with small samples. With twenty-five cases, for example, a Pearson correlation coefficient must equal .40 to be significantly different from zero at the .05 level. As sample sizes become larger and approach or exceed 100, this objection loses force.

### *The Intraclass Correlation*

A third method used to estimate the reliability of auditory threshold measurements is the intraclass correlation. This method overcomes one of the objections to the other methods inasmuch as it permits that variance to be partitioned into identifiable components which might otherwise be relegated to an error term. In many research problems the assumption is made that the total amount of variance in the obtained measures can be partly attributed to known causes (experimental treatments) and partly to unknown variations (sampling errors). As was pointed out earlier, the concept of reliability which stresses the degree of association or agreement between sets of measures is defined as the ratio of the predicted (known) variance to the total variance. The intraclass correlation is based on this relationship between variability sources and makes capital of the principles of analysis of variance which permit partitioning the total variance of a set of measures into its various components. A detailed treatment of this method is given by Haggard (6).

[4] *Subcommittee on Noise, unpublished data.*

The intraclass correlation method of estimating reliability can be used where only two repeat tests are available, but it is especially well suited to audiometric situations where three or more tests are available. In cases where a systematic trend is present among the means of successive tests as a result of learning, effects of aging, or experimental treatment, the variance due to the trend may be removed using a method developed by Alexander (1).

The intraclass coefficient, like the Pearson coefficient, ordinarily varies between zero and 1.00 (it never exceeds 1.00 but may take negative values under some conditions) which facilitates interpretation of the results and permits a direct comparison of the findings of different investigators.

While the intraclass correlation method carries with it a number of important advantages, there are certain precautions which must be observed in its application. The major rules or assumptions which underlie this method are that, 1) the various sources of variance in the total sample must be additive; 2) the observations within sets must be uncorrelated; 3) the variance within sets of observations should be approximately equal; and 4) the variations within experimental sets should be distributed normally.

These assumptions, with the possible exception of the fourth, should present little difficulty in a well designed experiment. While there has been a vast amount of audiometric research conducted in recent years, there is as yet no compelling evidence as to whether hearing sensitivity is distributed normally in the total population. It might reasonably be assumed that hearing sensitivity is normally distributed, even though most audiometric surveys have produced measurements skewed in the direction of hearing impairment, especially for the older age groups. Unquestionably, there are more physiological and environmental factors that contribute to hearing loss than there are factors that contribute to supernormal hearing, yet the empirical evidence on this question is inconclusive, however gratifying an intuitive explanation may be.

Because the normality of hearing sensitivity distributions is open to question, any statistical procedure used for analysis should be relatively independent of distribution characteristics. Fortuitously, the work of Norton (9, p. 78) and more recently of Boneau (2) has demonstrated that with the exception of certain extreme cases, normality of distribution of an attribute in the parent population and skewness in the scores of an experimental sample have little effect upon the accuracy of the

t and F tests associated with analysis of variance procedures. Since there is a monotonic relationship between F and R (intraclass correlation), the normality, or non-normality, of the scores in the experimental sample also has little effect on the accuracy of R. In those instances where extremely skewed scores are obtained in the experimental sample, it is possible to free the scores entirely from the influence of distribution characteristics by transforming the raw scores to ranks before computing the intraclass correlation.

## AN EMPIRICAL EXAMPLE

The purpose of this study was first, to illustrate the intraclass correlation as a method of estimating the reliability of repeat audiograms, and second, to compare the reliability of hearing threshold measurements obtained under four testing conditions.

### *Subjects:*

The subjects were seven males ranging in age from twenty to thirty-seven. Three were university students, and four were business college students. None reported having had their hearing tested previous to this experiment. The subjects were not screened on the basis of otological findings or noise exposure histories. Two subjects reported occasional tinnitus. Each man was paid for participating in the study.

### *Procedure:*

The subjects were tested in an IAC Model 401 sound treated booth equipped with a two-way voice communication system and a window through which the experimenter could observe the subjects. Four testing methods were used:

1) Modified Method of Limits, Button Response. The stimulus tone was presented at about 30 db above the subject's presumed threshold. (A stimulus tone having a duration of about one second was used for each of the three manual testing methods.) The attenuation was then quickly decreased in 10 db steps until the subject no longer responded to the stimulus tone. The attenuation was then decreased an additional 10 db below the point where the subject last responded, and then increased in 5 db steps until a response was obtained. Next, the attenuation was increased 10 db and a descending series was initiated, continuing down in 5 db steps until the subject failed to respond. The attenuator setting which represented the subject's threshold was usually fairly well located at this point. Verification of the threshold was obtained by bracketing the apparent threshold, that is, the stimulus tone

was presented 5 db above the apparent threshold and then 5 db below the apparent threshold. If the subject did not respond consistently, a new descending and ascending series was carried out using 5 db steps followed by bracketing of the apparent threshold for verification. This procedure was continued until the experimenter was satisfied that the threshold was accurately located. The threshold value recorded was that attenuator setting which in the opinion of the experimenter best represented the minimum level the subject was able to respond to.

2) Modified Method of Limits, Finger Response. This procedure was identical with the first, except that the subject was instructed to respond by raising his index finger when the stimulus tone was perceived. It was hypothesized that interpretation of the finger response might be more variable than a button response. When the finger is used to signal a response, it is possible for the subject to indicate uncertainty by partially raising his finger, whereas with a button response, the signal light is either on or off.

3) Ascending and Descending Series, Finger Response (Method of Minimal Changes). The test tone was first presented about 30 db above the subject's presumed threshold and then attenuated in 5 db steps until he failed to respond .The 5 db attenuator setting at which the subject responded was recorded as the descending threshold. The threshold was next approached in 5 db steps from about 10 db below the descending threshold. The ascending threshold was recorded as the attenuator setting at which the subject first responded. Each subject's threshold was crossed four times; twice ascending and twice descending. The threshold was taken as the mean of the four crossings .

The order in which the frequencies were tested for the first three methods was 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 cps. An Ambco Model 1150 audiometer was used to obtain the threshold for the three preceding methods.

4) Modified Békésy Method. A Rudmose ARJ-3 Békésy type recording audiometer was used to obtain the thresholds for this condition. The subjects responded to the stimulus tone by opening and closing a hand-held switch. The switch reversed the direction of travel of a motor driven attenuator that varied the intensity of the stimulus. When the tone was perceived, the subject pressed the spring-loaded hand-held switch which reversed the attenuator and decreased the stimulus intensity. When the signal was no longer perceived, the button was released, thereby increasing the stimulus intensity, and so on. The audiometer traced the threshold crossings at each of six test frequencies. Every thirty seconds,

the frequency was changed automatically. The frequencies were presented in the following order: 500, 1000, 2000, 3000, 4000, and 6000 cps.

The threshold values were read from the printed tracings in the following manner. The points at which the attenuator reversed its direction of travel were noted on the tracings for both the ascending and descending series. The hearing level value corresponding to the midpoint between the fourth highest reversal point for the ascending series and the fourth lowest reversal point for the descending series was taken as the threshold.

The threshold measurements for all conditions were recorded relative to ASA zero hearing level standards. The acoustic output of the earphones were calibrated prior to each test day using an Allison 3-A artifical ear fitted with NBS 9-A coupler and a Kellog Model A condenser microphone. A frequency count was made for all test frequencies on both audiometers using a Westport Electric frequency meter and counter. All frequencies met the ASA standards. The attenuators of both audiometers were checked for proper step intervals before and after the study and were found to be within ASA tolerances.

The four testing methods were presented in a counterbalanced order. Right and left ears were tested alternately for each subject during each test session, and the alternation was continued from session to session. Both audiometers used in the study were equalized for a single pair of TDH-39 earphones mounted in MX-41/AR cushions. A variable attenuator set at 30 db was placed in the line between the audiometers and the earphones to permit the testing of thresholds below the normal range of the audiometers.

The subjects were tested once a week for nine consecutive weeks. (Some subjects had difficulty in meeting their schedule, so there were a few cases in which the interval between tests for a given subject exceeded one week.) All frequencies and conditions were presented at each testing session. The subjects were given a practice trial for each of the four conditions on two consecutive weeks. The data from these trials were not used in the analysis.

*Results:*

A total of sixty intraclass correlation coefficients were computed for the various conditions and frequencies. The conditions were as follows: (2 ears x 3 manual testing methods x 8 frequencies) + (2 ears x 1 automatic method x 6 frequencies) = 60 conditions. Scores for the computational tables (corresponding to analysis of variance tables) were the threshold values for the testing conditions and frequencies. The intraclass correlation was computed from the formula

$$R = \frac{V_p - V_e}{V_p + (k - 1)V_e}$$ where

R = the intraclass correlation (reliability of scores for a single test)

$V_p$ = variance for persons

$V_e$ = error variance

k = number of tests

The intraclass correlation coefficients are shown in Table 1.

Table 1

Intraclass Correlation Coefficients (R) Obtained from Original Measurements of Nine Repeat Auditory Threshold Tests Under Four Testing Conditions

(N = 7)

| | | Frequency | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Test Method | 250 | 500 | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 |
| Right Ear | Modified Method of Limits, Button Response | .89 | .94 | .95 | .93 | .89 | .91 | .87 | .89 |
| | Modified Method of Limits, Finger Response | .90 | .96 | .96 | .92 | .93 | .89 | .92 | .92 |
| | Ascending and Descending Series, Finger Response | .83 | .96 | .93 | .93 | .89 | .93 | .93 | .93 |
| | Modified Békésy Method | - | .88 | .90 | .87 | .80 | .89 | .83 | - |
| Left Ear | Modified Method of Limits, Button Response | .87 | .89 | .94 | .84 | .85 | .82 | .55 | .82 |
| | Modified Method of Limits, Finger Response | .84 | .84 | .93 | .82 | .75 | .69 | .55 | .88 |
| | Ascending and Descending Series, Finger Response | .81 | .88 | .94 | .73 | .82 | .69 | .37 | .84 |
| | Modified Békésy Method | - | .79 | .93 | .84 | .85 | .84 | .49 | - |

The coefficients were consistently higher for the right ear than for the left ear at all frequencies and for all methods. There were some small but unimportant differences between testing methods. The correlations obtained from the left ear tended to vary more from frequency to frequency than did those from the right ear. The most striking result was found for 6 kc for the left ear. The mean value of the coefficients for all methods at this frequency was only .49. The corresponding value for the right ear was .89.

These results are almost identical with those obtained by Corso and Cohen (3) who determined the intraclass correlation for a sample of about thirty-five for three repeat tests using similar computational procedures. No explanation was offered to account for the discrepancy in reliability found between ears at 6 kc.

Inspection of the hearing level distributions in the present study showed that the dispersions at 6 kc were only about half of those found for the other frequencies. The distributions for all other frequencies were considerably skewed. It was evident that failure to screen the subject for this study permitted inclusion of two individuals, one with a low frequency conductive loss and the other with a high frequency loss. The result was skewed distributions at all frequencies except, unaccountably, at 6 kc for the left ear where all subjects showed relatively normal hearing levels.

A few randomly selected intraclass correlation coefficients with the deviant case omitted were computed. A typical result was that found for the right ear at 1 kc (method of limits, finger response) where the original coefficient computed for all subjects was .93. With the hearing loss case removed from the sample, the value of the coefficient dropped to .47. Since R is a measure of the relative homogeneity of the classes (individual scores from occasion to occasion) in relation to the total amount of variance in the table, a skewed distribution of hearing level scores will yield a higher value of R than will a nonskewed distribution. Similarly, symmetrical distributions having large dispersions will yield higher R's than symmetrical distributions having small dispersions if the homogeneity of classes is equal in both cases.

In situations where experimental controls are not used to obtain an otologically homogeneous sample it may be desirable to derive reliability estimates that are not subject to the influence of distribution characteristics. This can be accomplished by transforming the original hearing level measurements to ranks before computing the intraclass

correlation. The data of the present study were subjected to this transformation and additional reliability estimates based on ranks computed.

Inspection of the data in Table 1 suggested that before transforming the scores to ranks, certain computational economies could be made by combining the data for the various methods. Tests were applied (6, p. 20) to determine whether the differences between the reliability coefficients for the various testing methods were statistically significant. None of the differences were found to be large enough to reach the .05 level. In addition, two treatment by level analyses of variance (one for each ear) were computed to determine whether there were any significant differences among the threshold values obtained by the four testing methods. The results of these analyses indicated that the thresholds differed significantly among the tested frequencies, as would be expected, but the differences in thresholds among testing methods were not significant for either ear.

Since neither the threshold scores nor the reliability coefficients differed among the testing methods, the methods were combined within ears and the data treated as though the subjects had been tested on thirty-six occasions with a single method. The threshold values for each of the thirty-six occasions were converted to ranks (each frequency was treated separately as before) and intraclass correlation coefficients were computed using the ranked scores (6, p. 129). The estimates of reliability obtained from the rank ordered threshold scores were thus freed from the influence of distribution characteristics, although at the sacrifice of some precision as is typical of non-parametric methods.

Table 2

Intraclass Correlation Coefficients ($\hat{\rho}$) obtained from Thirty-six Measurements of Thirty-six Repeat Auditory Threshold Tests

($\bar{X}$ =7)

| Ear | Test Frequency | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 250 | 500 | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 |
| Right | .69 | .58 | .78 | .72 | .70 | .70 | .59 | .69 |
| Left | .66 | .59 | .74 | .79 | .72 | .78 | .56 | .83 |

Table 2 shows that the reliability coefficients based on ranked scores were consistently lower at all frequencies than the estimates from original scores. No systematic differences were found between ears except at 8 kc where the reliability for the left ear was substantially higher than for the right. At 6 kc where the original measurements yielded a pronounced difference in reliability favoring the right ear, the ranked scores showed almost equal reliability values for left and right ears.

## Discussion

The influence of distribution shape on the intraclass correlation should not necessarily be considered a defect of this method of determining reliability. Estimating the reliability of a set of measures involves the concomitant evaluation of a measurement instrument (and/or technique) together with a particular sample; the obtained result applies only to the given instrument and the given sample scores, whatever their distribution shape. In the example given above, the reliability coefficients derived from the original measurements are as meaningful as those derived from the same measurements when transformed to ranks. The reliability coefficients for the original measures were higher because with the skewed distributions the audiometric technique consistently discriminated one individual from another over trials. The coefficients would have been somewhat lower had the thresholds of all cases been more homogeneous, since the audiometric measurements would then have been less accurate in distinguishing one subject from the next over trials (assuming that the individual variability of the subjects over trials were the same in both cases). The values derived from the ranked measures are probably more representative of an otologically homogeneous group, since with ranked scores all individuals contributed proportionately to the total variance. A more desirable procedure for determining the reliability of a homogeneous sample would be to impose experimental controls, that is, to screen the subjects for negative otological status, noise exposure histories, or some other criteria, depending on the problem at hand.

The shape of the distribution of threshold measures in an experimental sample is of more importance when the investigator is concerned with making inferences about the reliability in the population from which the experimental sample was drawn. In such a case it is necessary for the distribution of sample scores to be similar to that of the parent population if valid inferences are to be drawn.

Of the numerous statistical procedures available for estimating the reliability of audiometric measurements, the intraclass correlation is the preferred method for most investigations because of its flexibility and generality of application. This method 1) can be applied in most cases where two or more serial audiograms are available (the method may not give accurate results with fewer than five subjects), 2) can be used analytically to identify non-random variation in scores, 3) expresses reliability as an index number that has a uniform meaning, 4) can be adapted, by means of raw score transformations, for use with samples that show peculiarities of score distribution, and 5) can be used for making inferences about population parameters where appropriate samples are available. For special cases, however, other methods for estimating reliability may be indicated. For example, the intraclass correlation may be inappropriate or impractical to compute when the number of cases is extremely large, or the investigator is concerned with the variability of individual subjects.

## SUMMARY

Various procedures for estimating reliability were reviewed and evaluated in terms of their implications for audiometry. The intraclass correlation was appraised as a general method suitable for a wide range of situations where reliability estimates are required for repeat audiometric measurements.

A reliability study was reported in which pure tone auditory threshold measurements were obtained on nine successive occasions for seven subjects using four testing methods. Intraclass correlation coefficients derived from original measurements were shown for the various test frequencies and methods. The correlation coefficients ranged in value from .37 to .96. No differences were found among the testing methods with respect to the obtained reliability estimates or hearing levels.

A procedure was illustrated for estimating the reliability of audiometric measurements freed from the influence of distribution characteristics. The auditory threshold measurements obtained in the study were transformed to ranks and new reliability estimates were derived using a variation of the intraclass correlation. These estimates ranged in value from .50 to .79.

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# A COMPARISON OF TWO METHODS OF ADMINISTRATION IN BEKESY-TYPE AUDIOMETRY

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In 1947 von Bekesy (1) designed a new self-recording audiometer with which the classic psychophysical method of adjustment was employed whereby the observer controlled the intensity of the stimulus as he traced back and forth across his threshold. While increasing experimental and clinical use of this device has attested to its value as a research and clinical tool in the area of auditory assessment, there have been discrepant reports in the literature concerning the relation of thresholds obtained from different methods of administration and of recording the threshold reading as well as the relation of Bekesy audiometer thresholds compared to those obtained by conventional pure tone methods.

In 1956 Corso (3) compared the absolute thresholds of 105 subjects obtained with a commercial audiometer (ADC 50-E2) and a Reger model of the Bekesy-type audiometer. He reported thresholds by conventional pure tone audiometry yielded better threshold values than the "midpoint" readings obtained by the Bekesy-type instrument. In the latter case, Corso's instructions to the subject required the individual to adjust the loudness of the tone so that it was "always just barely audible." In 1957 Burns and Hinchcliffe (2) in England also compared auditory thresholds as measured by conventional pure tone audiometry to those obtained by use of a Bekesy-type audiometer. In contrast to Corso's method, however, these authors required their subjects to adjust the intensity until the tone reached inaudibility in each cycle of operations. These two experiments revealed contradictory findings, since, in contrast to Corso, Burns and Hinchcliffe reported slightly better threshold values with self-recording audiometry. The British authors suggested this discrepancy may have resulted from the difference in method of instruction to their subjects, who were asked to take the tone to inaudibility in each cycle, while Corso's subjects kept the tone always just at the barely audible level.

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It would appear, therefore, that further clarification concerning the effect upon threshold produced by differing methods of administration of Bekesy-type audiometric testing is needed in order to compare results of experimenters and clinical workers from different laboratories. It was the purpose of the present investigation to determine the quantitative difference in threshold resulting from the two methods of instruction noted above. In addition, the experimental design permitted an observation of the influence exerted by factors of listener sophistication and rate of stimulus attenuation.

## SUBJECTS

A total of 42 young adults between the ages of 18 and 30 participated in the study. One-half were selected on the basis of prior knowledge of audiometry and in general could be called laboratory-trained listeners, while the other half were untrained or inexperienced listeners insofar as pure tone audiometry was concerned. Each subject evidenced normal hearing on the basis of a pure tone screening test at 10 db *re* normal threshold at octave intervals from 250 to 4000 cps.

## INSTRUMENTATION AND TEST ENVIRONMENT

Each subject was screened on a commercial audiometer of the discrete frequency type (ADC SC-1). Hearing thresholds for the present study were obtained using a Bekesy-type self-recording automatic audiometer (Grason-Stadler Model E-800). Both audiometers were equipped with TDH-39 earphones and MX 41/AR cushions. Only one earphone on each audiometer was used for purposes of testing and calibration to permit maximum calibration standardization. To determine constancy of the sound pressure level output of the test phones for each audiometer, a reading was taken with the Allison Model 300 Audiometer Calibration Unit on each day of testing. Mean errors from the standard SPL at each test frequency were computed with resulting correction factors applied to the group data. Standard deviations for the mean error in SPL output were 1.7 db at 250 cps, 1.9 db at 1000 cps, and 2.1 db at 4000 cps.

Built into the Bekesy audiometer were two speeds of attenuation which resulted in a rate of change in intensity of the stimulus at 4.5 db per second and 2.5 db per second. Both speeds were used in testing each subject at each of the three test frequencies.

All Bekesy tests were administered in an anechoic chamber for which the ambient noise level was 24 db *re* .0002 dyne/cm$^2$ as measured by a General Radio Type 1551-A Sound Level Meter. The earphones and push button attenuator control switch for use of the subject in the test chamber

were connected to the Bekesy audiometer in the control chamber by wires passing through conduits in the wall of the anechoic chamber. The subject was seated in the center of the chamber facing two signs on the wall at about five feet from him. One sign read "Press button to make tone softer," and the other read "Release button to make tone louder." In addition, a television camera was mounted within the anechoic chamber and connected to a viewing screen in the control room for purposes of maintaining visual contact with the subject being tested.

## TEST PROCEDURE

Each subject was given a brief explanation of the problem under study and the principles of the Bekesy audiometer test were explained, after which a manual demonstration by the examiner permitted the subject to see a typical cycle of operation with this instrument. This orientation, which allowed the subject to understand what he would be doing by operating the attenuator switch while seated in the anechoic chamber, was considered an important means of eliminating subject error in the testing situation.

For the test each subject was told to hold the attenuator key switch in the hand in which it would feel most comfortable and in a position that would allow instant compression or release of the switch. No mention was made to the subject concerning the change of attenuation speed, since this change was accomplished by the examiner and no purpose was thought to be served by calling attention to this aspect of the test.

In the practice session two discrete frequencies, 500 and 2000 cps, were used for familiarization with the procedure for adjustment. The practice session was conducted with the test phone over the ear contralateral to the pre-selected ear for recording thresholds for the actual test frequencies. At each of the two practice frequencies the subject was given an opportunity to keep the tone always just barely audible and also to take the tone to inaudibility. Following each practice session the headphones were removed and the subject was given a five-minute rest period before the testing resumed.

In the actual test session three discrete frequencies, 250, 1000, and 4000 cps were used. The variables of (1) tested ear, (2) rate of attenuation, (3) frequency and (4) set of instructions for adjustment presented themselves in a rather complex arrangement. To eliminate the possibility of any of these variables being presented first in every sequence, a form order sequence was constructed composed of the four variables for Group I, or the sophisticated listeners. The identical sequence was used for

Group II, the unsophisticated listeners. With 90 seconds allowed for each testing condition the total amount of time that each subject spent in tracing his threshold for recording purposes was 13 minutes. The basic pattern established for one frequency remained the same for the other two frequencies for any single individual.

The following set of directions was given orally to each subject for keeping the tone just barely audible:

> "Now you will hear a tone that does not get higher or lower in pitch. Your task will be to adjust the loudness of this tone so that you can always just barely hear it. *Never let it fade away completely.* When you think it is going to fade away so that you won't be able to hear it, release the switch instantly so that it will get louder. Remember to adjust the loudness so that you can always just barely hear it. This is very important. As soon as you hear the tone, adjust it as I have just instructed. These signs will help you to remember the directions. Are there any questions?'

For crossing the threshold and taking the tone to inaudibility, the following directions were given:

> "Now you will hear a tone that does not get higher or lower in pitch. Your task will be to adjust the loudness of this tone so that it will become softer and fade away. The *instant* it fades away you willrelease the switch until you can hear the tone again. As soon as you hear the tone again, press the switch so that the tone will begin to fade away. It is important that the instant you do not hear the tone to release the switch so that the tone will get louder. As soon as you hear the tone, adjust it as I have just instructed. These signs will help you to remember the directions. Are there any questions?"

Three points along each 90 second tracing, 30, 55, and 80 seconds, were selected along the abscissa of the chart, from which threshold measurements were calculated. For obtaining a threshold measurement the following procedure was inaugurated. The midpoints of the two excursion lines on either side of that one which crossed at each of the selected time points above were connected by a straight line. The threshold value recorded was that db level represented at the intersection of this line with the vertical reference line representing one of the three time interval periods. This procedure was accomplished at each of the three prescribed time interval points, and an average of the three was recorded as the mean threshold for that 90 second period and for that particular frequency.

## RESULTS

The combination of conditions tested resulted in 12 mean threshold values for each subject, as follows:

At 250 cps

1. Tone always audible with fast rate of attenuation
2. Tone always audible with slow rate of attenuation
3. Tone to inaudibility with fast rate of attenuation
4. Tone to inaudibility with slow rate of attenuation

At 1000 cps

5. Tone always audible with fast rate of attenuation
6. Tone always audible with slow rate of attenuation
7. Tone to inaudibility with fast rate of attenuation
8. Tone to inaudibility with slow rate of attenuation

At 4000 cps

9. Tone always audible with fast rate of attenuation
10. Tone always audible with slow rate of attenuation
11. Tone to inaudibility with fast rate of attenuation
12. Tone to inaudibility with slow rate of attenuation

The mean thresholds for the two listener groups are presented in Table 1 in such a manner that an immediate comparison of results obtained from the two methods of administration is possible. All the data obtained by the various conditions of testing within each group of subjects were first subjected to an analysis of variance. By means of an analysis of repeated measurements on several independent groups (4, p. 288), highly significant $F$ values of 9.4 for the sophisticated listeners and 9.7 for the unsophisticated listeners were obtained. Additional analysis revealed that interaction factors between (1) method of instruction, (2) speed of intensity attenuation, and (3) frequency tested were not statistically significant. In view of the significant $F$ values, however, $t$ tests of significance between specific variables were done to determine which ones were contributory to the differential results.

Since the major objective of the present study was to discover if varying the method of instructions to the subject in Bekesy audiometry would produce a significant difference between resultant thresholds as denoted by the midpoints of the excursion patterns, $t$ tests comparing the two methods were of first concern. When the $t$ test formula for matched groups was applied (5, p. 153),

$$t = \frac{\Sigma D}{\sqrt{\frac{N\Sigma D^2 - (\Sigma D)^2}{N - 1}}},$$

TABLE I

Summary of Mean Thresholds in db *re* Normal (1936 U. S. Public Health Survey) for the Sophisticated and Unsophisticated Listeners Tested by Automatic Audiometry Using the Two Methods of Instructions and Two Rates of Attenuation at Three Frequencies.

| Frequency | Method of Instruction | Mean | SD | Mean | SD |
|---|---|---|---|---|---|
| | | Sophisticated Listeners-Group I | | | |
| | | Attenuation Rate 4.5 db/Sec. | | Attenuation Rate 2.5 db/Sec. | |
| | Aud | 3.1 | 5.6 | 5.1 | 6.1 |
| 250 cps | | | | | |
| | Inaud | -3.5 | 5.4 | -1.9 | 5.0 |
| | Aud | -4.7 | 7.6 | -3.7 | 7.2 |
| 1000 cps | | | | | |
| | Inaud | -10.1 | 6.5 | -9.4 | 6.9 |
| | Aud | 8.6 | 8.9 | 9.3 | 9.2 |
| 4000 cps | | | | | |
| | Inaud | 2.4 | 7.3 | 4.7 | 8.0 |
| | | Unsophisticated Listeners-Group II | | | |
| | | Attenuation Rate 4.5 db/Sec. | | Attenuation Rate 2.5 db/Sec . | |
| | Aud | 7.0 | 5.9 | 7.5 | 6.8 |
| 250 cps | | | | | |
| | Inaud | 4.0 | 7.7 | 3.5 | 7.9 |
| | Aud | -1.0 | 8.1 | -0.3 | 6.7 |
| 1000 cps | | | | | |
| | Inaud | -4.2 | 6.9 | -3.1 | 6.4 |
| | Aud | 8.7 | 10.8 | 9.0 | 10.5 |
| 4000 cps | | | | | |
| | Inaud | 3.9 | 10.7 | 4.9 | 9.9 |

results for the 12 comparisons showed in every case a significant *t* value at the .01 level. In the majority of instances a higher *t* value resulted for the sophisticated listeners as compared to the unsophisticated listeners in situations where the other two variables of frequency and speed of attenuation remained constant. The mean differences in actual hearing levels for the two methods are shown in Table 2.

TABLE 2

Mean Differences in Bekesy Thresholds Obtained When Subjects Were Instructed to Use the Point of Transition to Inaudibility Rather than the Point Where Tone Remained Minimally Audible as the Threshold Criterion.

| | Attenuation Rate 4.5 db/Sec. | | Attenuation Rate 2.5 db/Sec. | |
|---|---|---|---|---|
| | Sophisticated Group I | Unsophisticated Group II | Sophisticated Group I | Unsophisticated Group II |
| 250 cps | 6.6 db | 3.0 db | 7.0 db | 3.0 db |
| 1000 cps | 5.4 db | 3.2 db | 5.7 db | 3.0 db |
| 4000 cps | 6.2 db | 3.8 db | 4.6 db | 4.1 db |

Second, the differences between the two rates of attenuation (2.5 db and 4.5 db per second) were also subjected to *t* tests, using the difference method for matched conditions. Significant differences were observed for only four of the 12 conditions, but in all cases the faster rate of attenuation yielded a slightly better threshold, as may be noted in Table 3. It was of interest to note that changes in speed of attenuation significantly affected the threshold of the sophisticated listeners in three of six conditions, while only one significant *t* score obtained for the six conditions for the unsophisticated listeners. There was, however, no established pattern nor consistent trend for either group with respect to speed as combined with the other variables.

TABLE 3

Mean Differences in Bekesy Thresholds Obtained When the Faster Attenuation Rate Was Contrasted to the Slower Attenuation Rate of the Test Signal.

| | Tone Retention at Minimal Audibility | | Tone to Transition of Inaudibility | |
|---|---|---|---|---|
| | Sophisticated Group I | Unsophisticated Group II | Sophisticated Group I | Unsophisticated Group II |
| 250 cps | 2.0 db | 0.5 db | 1.6 db | -0.5 db* |
| 1000 cps | 1.0 db | 0.7 db | 0.7 db | 1.1 db |
| 4000 cps | 0.7 db | 0.3 db | 2.3 db | 1.0 db |

* One reversal in which the slower attenuation rate (2.5 db/sec) yielded the better mean threshold value.

Third, in order to distinguish differences between the two groups of listeners - that is, sophisticated and unsophisticated - the *t* test of significance for differences between unmatched groups (5, p. 156)

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{s^2 \frac{N_1 + N_2}{N_1 N_2}}}$$

was applied to the data. While 11 of 12 comparisons favored the trained listener group for obtaining the better threshold, a significant difference at the .05 level occurred in only five of the 12 conditions. The mean differences in hearing levels between the two groups under the various test conditions are shown in Table 4. Inspection of the data showed further that significant differences occurred between groups for three of four comparisons at 250 cps, two of four at 1000 cps, but none at 4000 cps. The loci of significant *t* scores comparing listener sophistication suggested also that larger differences between the two groups may occur when the task requires taking the tone to inaudibility in each cycle of operations. In other words, while the trend for better thresholds for sophisticated listeners was quite consistent, it was most marked in the tone to inaudibility method.

TABLE 4

Mean Differences in Bekesy Thresholds Obtained by the Sophisticated Listener Group When Compared to the Unsophisticated Listener Group.

| | Tone Retention at Minimal Audibility | | Tone to Transition of Inaudibility | |
|---|---|---|---|---|
| | Atten'tn Rate 4.5 db/Sec. | Atten'tn Rate 2.5 db/Sec. | Atten'tn Rate 4.5 db/Sec. | Atten'tn Rate 2.5 db/Sec. |
| 250 cps | 3.9 | 2.4 | 7.5 | 5.4 |
| 1000 cps | 3.7 | 3.4 | 5.9 | 6.3 |
| 4000 cps | 0.1 | -0.3* | 1.5 | 0.2 |

* One reversal in which the Unsophisticated Listener Group obtained the better threshold value.

As part of the present experiment, it was considered pertinent to obtain subjective opinions from the subjects concerning the comparative ease with which they administered the test to themselves under the two methods. Without exception the subjects stated that it was easier to take the tone to inaudibility in each cycle of operations rather than having to keep it always just barely audible. Apparently there may have been considerable strain on the individual who was conscientiously trying to maintain the tone at the just audible level. Although Corso (3) stated he believed the terminology used in instructing a subject to keep the tone always audible would be more understandable for the unsophisticated listener, this advantage may well be offset by the greater difficulty in performing the test.

## SUMMARY

The present study was undertaken to evaluate the effect exerted on the hearing threshold by two methods for the adjustment of a pure tone by the listener when using automatic audiometry. At the same time an attempt was made to assess the relative interplay that two rates of intensity change plus listener sophistication had upon the threshold. The data resulting from the tracing thresholds of the 42 subjects, each of whom was tested for 90 seconds under each of 12 different conditions, were subjected to statistical analysis to determine the significance of the effects of the several variables upon hearing thresholds of the two groups of listeners.

The results clearly indicated a significant difference in such thresholds for 42 normal hearing individuals, with the tone to inaudibility method yielding the superior hearing levels. This finding appeared to be independent of the amount of previous experience the listener had had in the area of audiometry.

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# VIGILANCE FOR CUTANEOUS AND AUDITORY SIGNALS

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Changes in efficiency of responding as a function of time on task have been found for both visual and auditory stimuli under some conditions (Broadbent, 1958; McGrath, et al, 1959; Frankmann and Adams, 1960). Broadbent (1958) has suggested that performance for Os attending to auditory stimuli is less susceptible to such a decrement, for it is harder for Os to *not* attend to an auditory stimulus than a visual one. This has not been clearly demonstrated, however. Elliot (1957) found no change in effective threshold for auditory stimuli as a function of time on task. On the other hand, progressive increases in failures of detection were reported when Os were required to detect changes in duration (Mackworth, 1950), frequency (Solandt and Partridge, 1946), or intensity (Buckner, et al, 1960). Loeb and Schmidt (1960a, b) found no temporal trend for failures of detection when Os were merely to report the presence of a weak low-frequency auditory stimulus, but there was a progressive increase in response time.

The cutaneous modality may be useful in situations where the visual or auditory channels are not available. That cutaneous signals could be used successfully for the reception of messages was demonstrated by Geldard (1957), utilizing mechanical vibration of the skin. Hawkes (1960a) has further suggested that electrical cutaneous stimulation offers advantages over mechanical vibration for signaling purposes. The detectability of cutaneous stimuli relative to vigilance performance with auditory or visual signals, however, has not been evaluated. It was noted in a recent symposium (Hawkes, 1960b) that no data are available on vigilance for cutaneous stimuli, and that such data for cutaneous vs. auditory or visual signals are important criteria for assessing communications efficiency with these stimuli.

The present experiment was undertaken to investigate vigilance with mechanical vibration or electrical stimulation of the skin vs. auditory stim-

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uli. Male and female Os were required to detect the occurrence of infrequent stimuli of a weak intensity level; a weak intensity level was chosen inasmuch as vigilance decrement is more readily apparent in such situations (Broadbent, 1958; Loeb and Schmidt, 1960a, b).

## APPARATUS AND PROCEDURE

The electrical cutaneous stimulus was the output of a Grason-Stadler random-noise generator, amplified by a McIntosh MC-30, and matched to the impedance of the skin by a UTC Model LS-12 transformer. Stimuli were presented to O through an active electrode of 12 mm. diameter resting on the palm, and thence to an inactive strap electrode on the forearm. The E controlled the current level via a potentiometer; current to O was computed from the voltage drop across a 100-ohm shunt resistor.

The mechanical vibratory cutaneous stimulus was the random-noise signal, amplified by a McIntosh MC-60, presented to O via a Goodmans V-47 vibrator with a contact surface of 6 mm. diameter resting on the palm. The auditory stimulus was produced by feeding the random-noise generator output through a General Radio attenuator into a pair of Permoflux PDR-8 earphones.

The duration of each signal was 0.5 sec., and the rise time was approximately 1 $\mu$sec. (Random noise was used as a stimulus in this experiment in order to be able to produce very rapid rise times without perceptible switching transients.) The inter-stimulus interval was 30, 45, 60, 75, 90, 105, or 120 sec. Within each block of seven successive signals, each interval was employed once; within this limitation, the value for a given trial was determined randomly. There were ten successive blocks of trials in each session.

The electrical cutaneous RL was determined for each O at the beginning of a session. A weak intensity level, 1.6 db SL was chosen for use in the sessions involving electrical stimulation of the skin; this intensity level had been used in a previous investigation of $\Delta I/I$ (Hawkes, 1961). In sessions with auditory or mechanical vibratory signals, O was asked to equate the subjective intensity to that of the 1.6 db electrical cutaneous stimulus (see Stevens, 1950). This procedure assumes, though it has never been demonstrated in this context, that signals of equal subjective intensity are equal in detectability (cf. Green, 1960).

The Os were 12 male and 12 female students at the University of Louisville. The O was seated in a sound-deadened room with an ambient noise level of about 30 db. Earphones contained in Willson earmuffs (with an attenuation of room noise of 15 - 30 db, dependent on

frequency) were worn in all sessions, and O rested his palm on the electrode and the mechanical vibrator, irrespective of the type of signal being presented in a given session. All Os participated in three sessions, with the individual session being devoted to use of mechanical vibratory, electrical cutaneous, or auditory stimulation. Order of presentation was counterbalanced.

An Argus closed-circuit television system was used for observation of O to avoid a spurious number of misses due to falling asleep. The TV camera was visible to Os, and they were informed that they would be watched via TV.

All Os were paid two dollars for each of the three experimental sessions. They were instructed to respond as rapidly as possible whenever a signal occurred. A twenty dollar prize was offered to the individual with the "best" overall performance.

Responses were made by pressing a telegraph key. Errors of commission and omission were recorded by E; latency of response to the nearest msec. was recorded from a Standard Electric timer. Earlier experimentation indicated that almost all responses were made within 1.0 sec. If O did not respond within 3.0 sec., he was credited with a missed response in this study; all responses outside of the 3.0 sec. post-signal interval were scored as false responses.

## RESULTS

Means of the median latencies for each of the ten blocks of trials as a function of modality and sex are shown in Figure 1. Statistical significance of the experimental variables was tested by a complex analysis of variance; results are summarized in Table 1.

Table 1

Analysis of Variance Summary

| Variable | df | MS | F | P | Error Term |
|---|---|---|---|---|---|
| Sex | 1 | 879,412 | 1.15 | | 1 |
| Blocks of Trials | 9 | 7,661 | 1.09 | | 2 |
| Modality | 2 | 4,834,108 | 29.11 | <.01 | 3 |
| M x B | 18 | 551,945 | 76.71 | <.01 | 4 |
| M x S | 2 | 132,731 | - | | 3 |
| B x S | 9 | 3,531 | - | | 2 |
| M x B x S | 18 | 35,157 | 4.88 | <.01 | 4 |
| **Error Terms** | | | | | |
| 1 (Between Os) | 22 | 765,131 | | | |
| 2 (Within) B & S | 198 | 7,549 | | | |
| 3 (Within) M & S | 44 | 166,124 | | | |
| 4 (Within) M &B& S | 396 | 7,195 | | | |

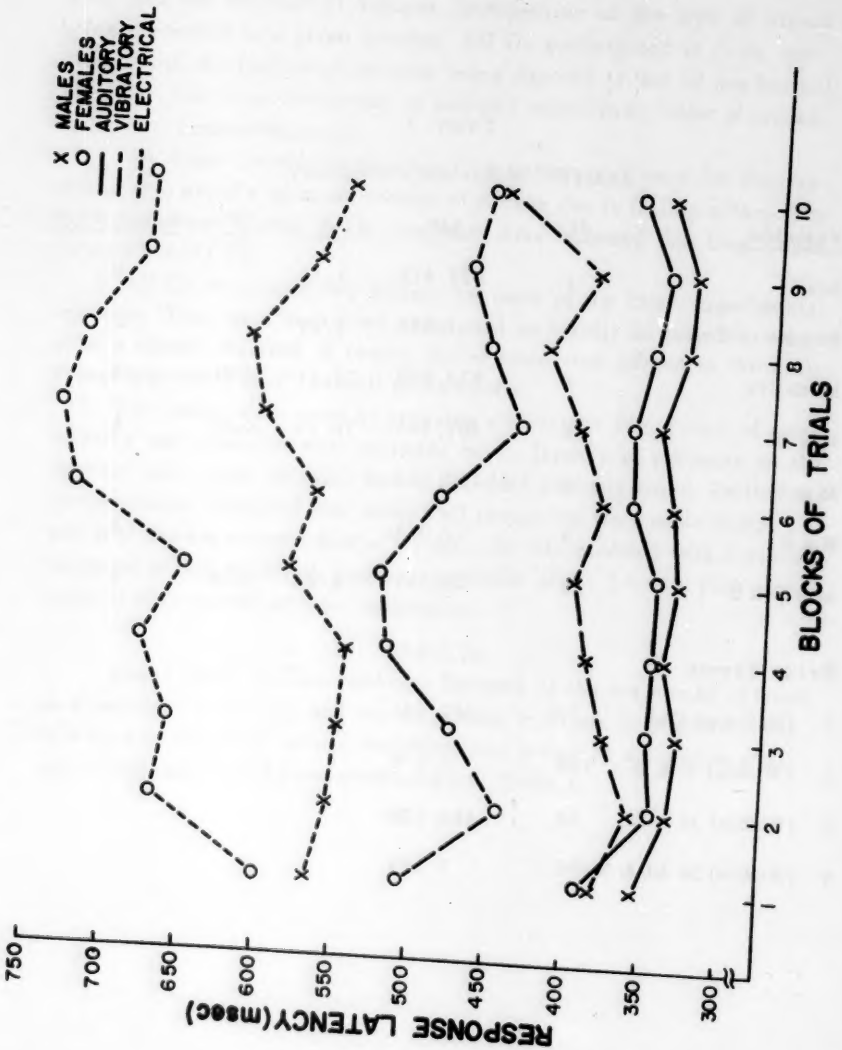


Fig. 1. Mean latency of response as a function of modality for 12 female and 12 male *O*s.

Several trends are apparent. Differences between median latencies when responding to signals involving different sensory modalities were statistically significant ($p<.01$). Response time was greatest for electrical cutaneous stimuli and smallest for auditory stimuli. Although the mean of the median latencies for males was consistently lower on each block of trials on each modality than that for females, the overall sex difference and the interactions of modality and sex and of blocks of trials and sex were not statistically significant.

No consistent trend for a latency change with time on task is apparent in Fig. 1, and further the variance between blocks of trials was not significant. However, the interactions of blocks of trials with modality and with modality and sex are significant ($p<.01$). An appreciable increase in response time for females responding to electrical stimuli is apparent on the later blocks of trials (see Fig. 1), and this increase is apparently responsible for the size of the interactions observed. This difference is statistically significant, moreover, only for the second half of the session. A Pearson correlation was computed between overall means of median latencies for each modality. Correlations between auditory vs. electrical cutaneous response time was 0.60, between mechanical vibratory and electrical cutaneous was 0.63, and between auditory and mechanical vibratory was 0.69. All values were significant ($p<.01$).

Errors of omission (failures to detect the signal) are given for each O and each modality in Table 2. Inasmuch as the distribution of misses was obviously skewed, no summarization by computation of medians or means was attempted. Instead, because misses were relatively few, they were tabulated in blocks of 14 trials (vs. seven for the latency data), each block corresponding to a 17.5 min. period.

Table 2

Errors of Omission for Each O and Each Modality

| O | Blocks of Trials 1 & 2 | | | 3 & 4 | | | 5 & 6 | | | 7 & 8 | | | 9 & 10 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | E. | V. | A. * | E. | V. | A. | E. | V. | A. | E. | V. | A. | E. | V. | A. |
| **FEMALE** | | | | | | | | | | | | | | | |
| 1 | | | | | | | | | | | | | 4 | | |
| 2 | | | | | | | | | | 5 | | | 2 | | |
| 3 | | | | | 10 | | | 2 | 10 | 2 | 8 | | 4 | 10 | |
| 4 | 6 | | | 5 | | 1 | | 4 | | 4 | | | | | |
| 5 | | | | 1 | | | | | | 1 | | | 1 | | |
| 6 | | 1 | | 3 | | | | 1 | 2 | 5 | 1 | | 4 | | |
| 7 | | | | | | | | | | 1 | | | 2 | | |
| 8 | | | | | 3 | | | | | | | | | 1 | |
| 9 | 4 | | | 2 | | | | 4 | | 5 | | | 1 | | |
| 10-12 | NONE | | | | | | | | | | | | | | |
| **MALE** | | | | | | | | | | | | | | | |
| 1 | | | | 1 | | | | | | 1 | | | 1 | | |
| 2 | | | | | | | | | | | | | | 3 | |
| 3 | | | | | 1 | | | | | 1 | | | 1 | | |
| 4 | 1 | | | 4 | 4 | | | 4 | 1 | 2 | | | 2 | | |
| 5 | | | | | | | | | | | 1 | | | | |
| 6 | 1 | | | 2 | 2 | | | 5 | | 3 | | | 6 | | |
| 7 | | | | | | | | | | | | | 1 | | 1 |
| 8 | | 1 | | | | | | | | | | | | | |
| 9 | | | | 1 | | | | | | | | | | | |
| 10-12 | NONE | | | | | | | | | | | | | | |

*E. Electrical Cutaneous
V. Mechanical Vibration
A. Auditory

It should be noted that three females and three males never failed to detect a signal when responding to stimuli in any modality. Even though misses were somewhat more numerous among females, the difference was not statistically significant (Mann-Whitney U test). Male and female data were combined for analysis of the omission data.

Differences in numbers of misses in different blocks of trials were tested by the Wilcoxon T test. The apparent tendency for misses to increase in frequency in the later blocks of trials was not significant. There were significantly more misses of electrical signals than auditory ones ($p<.01$), more misses of electrical stimuli than mechanical vibratory($p<.05$), and more failures to detect mechanical vibratory signals than auditory ones ($p<.05$). Only three auditory signals were missed out of the 1680 signals presented.

False responses (errors of commission) are presented in Table 3. Analysis of these data was similar to the above. Again, no significant differences between male and female Os were noted. False responses were significantly less numerous when Os were responding to auditory stimuli than when they were responding to electrical or mechanical vibratory ones ($p<.05$ and $<.01$, respectively). Differences in errors of commission for electrical vs. mechanical vibratory stimuli were not significant.

Table 3

Errors of Commission for Each O and Each Modality

| O | Blocks of Trials 1 & 2 E. | V. | A.* | 3 & 4 E. | V. | A. | 5 & 6 E. | V. | A. | 7 & 8 E. | V. | A. | 9 & 10 E. | V. | A. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **FEMALE** | | | | | | | | | | | | | | | |
| 1 | | | | | | | 1 | | | | | | 1 | | |
| 2 | | | | 1 | | | | | | | | | | | |
| 3 | 5 | | | | 5 | | | 7 | | | 4 | | | 3 | |
| 4 | 1 | | | | 1 | | | | | | | 1 | | | 1 |
| 5 | | | | | | 2 | | | | | 1 | 1 | | 1 | |
| 6 | | | | | 1 | | | | | 3 | | | 1 | | |
| 7 | | | | 3 | | | | | | 1 | | | | | |
| 8 | 2 | 1 | | 1 | 1 | | 3 | | | 2 | | | | | |
| 9-12 | NONE | | | | | | | | | | | | | | |
| **MALE** | | | | | | | | | | | | | | | |
| 1 | 1 | | | 2 | | | | | | | 1 | | 4 | | |
| 2 | | | | | | | | 1 | | | 3 | 1 | | 1 | |
| 3 | | | | 1 | | | 1 | | 1 | | 1 | | 1 | | |
| 4 | | 1 | | | | | | | | | 1 | | | | |
| 5 | | | | | | | | | | | 1 | | | | 1 |
| 6 | | | | | | | | | | 2 | 4 | | | | |
| 7 | | 2 | | | | | | | | | 1 | | | 1 | |
| 8 | 1 | 7 | | | 4 | | | | | | | | | 1 | |
| 9-12 | NONE | | | | | | | | | | | | | | |

* E. Electrical Cutaneous
V. Mechanical Vibration
A. Auditory

## DISCUSSION

Failure to find an increase in errors of omission as a function of time on task seems to be characteristic of performance when O responds only to the presence of a signal. Loeb and Schmidt (1960a, b) have previously reported this for responding to low-frequency tones, and the present study indicates that the same is true for white noise and for mechanical vibratory or electrical stimulation of the skin. In addition, Elliot (1957) has shown that no change in effective absolute threshold with time on task occurs with auditory stimuli. Performance decrement has been found only in situations where Os were asked to make differential discriminations; a change in duration (Mackworth, 1950), frequency (Solandt and Partridge, 1946), or intensity (Buckner, et al, 1960).

If the performance measure is response time (latency), however, then a performance decrement as a function of time on task may occur. The present study demonstrates such a decrement for females responding to electrical cutaneous stimuli, and Loeb and Schmidt (1960a, b) reported a progressive increase in response time to faint pure tones. It is uncertain why such an increase occurred for auditory stimuli in the earlier studies and not in this one. However, the signals employed in the present study were somewhat higher in intensity (approximately 20 db SL vs. 10 db SL used by Loeb and Schmidt), shorter in rise and decay times, and broader in bandwidth. Further experimentation will be needed to establish the causes of the differing results.

A significant sex difference was apparent in this study only for response time to electrical cutaneous stimuli. Females exhibited a progressive increase in latency with time on task for this condition, but males did not. Differences in reaction time might lead one to expect vigilance to be superior for males, inasmuch as they have a shorter RT (Woodworth and Schlosberg, 1954, p. 36). Whittenburg, et al (1956), reported that females had fewer failures of detection on the Mackworth clock task, but an earlier report on the same data (Whittenburg and Ross, 1953) noted a somewhat smaller latency increase for males. Bakan (1955) reported no significant sex differences on a visual vigilance task, but there was a tendency for females to perform at a higher level ($p=.10$)[1]. An explanation of these apparently conflicting results is not readily apparent.

[1] *Personal communication.*

The intersession correlations for the latency measure were appreciable (0.60 - 0.69) and significantly high ($p<.01$). The correlations between numbers of misses in the visual and auditory sessions in the study by Buckner, et al, was only 0.30 under alerted conditions and 0.24 under watchstanding conditions; intersession correlations for a given modality, however, were comparable to the present values, 0.74 for the visual mode and 0.67 for auditory.

The appreciable inter-modality latency correlations, the small or negligible tendency for latencies to increase with time on task, and the relatively small number of errors under the least favorable (electrical cutaneous) condition, all indicate that any of the sensory channels investigated may be employed in most cases for a simple monitoring task. However, under these conditions, monitoring of electrical cutaneous signals is clearly inferior to that for auditory and mechanical vibratory stimuli were inferior to auditory. Further research should reveal whether or not this is equally true when O's task is to detect a change in the stimulus and whether there are still significant inter-sensory differences when signals of moderate intensity, rather than relatively faint ones, are to be detected.

## SUMMARY AND CONCLUSIONS

Twelve male and twelve female college students were asked to respond as rapidly as possible to relatively faint auditory, mechanical vibratory, and electrical cutaneous signals, occurring aperiodically in different sessions of approximately 90 min. duration. No progressive increase in latency or number of errors was noted for males under any condition, or for females when responding to auditory or mechanical vibratory stimuli. There was a progressive increase in response time to electrical cutaneous stimuli for females. Latency was generally highest for the electrical signals and smallest for the auditory ones; differences between modalities were significant. Similarly, the number of failures of detection was greatest for electrical signals and smallest for auditory ones. Though the differences are significant, failures of detection for all signals were relatively rare. False responses, again rare, were significantly fewer when Os were responding to auditory signals than when they were presented mechanical vibratory or electrical cutaneous ones.

It was concluded that auditory or cutaneous signals will generally be usable in the situation where the observer's task is to detect the presence or absence of a signal.

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# REACTION TIME, DIFFERENCE LIMEN AND AMPLITUDE OF EXCURSION ON NORMAL BEKESY AUDIOGRAM

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Although the Bekesy audiometer (1) can produce threshold values for a continuous sweep across the frequency range, more interesting are threshold tracings as a function of time, and size of excursions around threshold either as a function of frequency or of time.

Studies concerned with threshold as a function of time were done by Reger and Kos (19) and Lierle and Reger (10) in which temporary threshold shift (TTS) was described as a threshold change with continued exposure to near threshold sound. The TTS phenomenon apparently may occur with or without reduction in excursion width. Recently, Jerger (8) showed relationships between aural pathologies and differences in threshold responses to steady state and pulsed tones produced by the Bekesy audiometer for fixed frequencies as a function of time. His interpretations of responses were based largely on what appeared to be presence or absence of TTS.

Corso (2, 3) reported studies of Bekesy thresholds among normals leading to the conclusions that testing time and attenuation rate do not affect threshold at 1000 cps, reliability of threshold is maximum when using a slow attenuation rate, thresholds for pure tones are more acute by 0.5 db to 15 db using regular audiometry than when reading the midpoints of Bekesy audiogram excursions (but not when reading the peaks), and thresholds obtained by regular audiometry are less variable than Bekesy audiogram thresholds. Later Corso and Wilson (4) found that for normals best validity and reliability were obtained using 1.5 db per second attenuation and eleven minute testing time in contrast to faster attenuation rates and shorter testing times. Continuous or pulsed tones were not found to be different with respect to reliability and validity.

Regarding magnitude of excursions around threshold, Corso (2) found that 0.5 db and one db attenuation rates did not produce signifi-

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cantly different mean size of excursions (6.28 db and 6.29 db respectively), but that a two db attenuation rate produced significantly larger mean excursions (8.84 db). Reger (18) found six to eight db to be the normal range of excursions for normals, Lundborg (11), using attenuation at 140 db per minute found the range for normals to be five to twenty db, with a majority varying between six and nine db. Bekesy (1) reported ten db excursions when using ninety db attenuation per minute, ten to fifteen db excursions when using 140 db attenuation per minute and fifteen db excursions when using 220 db attenuation per minute. Palva (16) found excursions five to fifteen db wide (using one db attenuation steps at 140 db per minute attenuation rate) for normals, conductive losses and non-recruiting ears; later (17) he found excursions for normals to average on the order of eight to ten db, and the range to be from two to twenty db. Landes (9) found excursions for normals between approximately five and twelve db when using standard Bekesy-type audiometer apparatus. Epstein (5) reported four to nine db excursions among normals using one db per second attenuation rate, and five to seventeen db excursions using four db attenuation rate. He also mentioned that some subjects appeared to be "wide swingers" and others were typically "narrow swingers".

Reduction in width of excursions in Bekesy tracings is commonly seen in pathological ears for the higher frequency range. This has been interpreted as recruitment, or evidence of reduced difference limen associated with the presence of recruitment (1, 18). McLay (14) said excursions less than three db indicate recruitment while excursions five db or more do not. Lundborg (11) found reduced Bekesy audiogram excursions to be typical of persons with recruitment. However, it has been observed that not infrequently excursions of a non-recruiting ear are small and excursions of a recruiting ear are relatively large. For example, McLay (14) found that nine of 52 ears with recruitment according to the loudness balance test did not show reduced excursions on the Bekesy audiogram. Landes (9) found that only about 32 per cent of the recruiting ears he used had excursions less than five db, while the balance had excursions greater than five db. Palva (17) divided his subjects according to type of recruitment pattern; for the higher frequency range most asymptotic recruiters showed excursions smaller than five db and the incomplete recruiter group showed small excursions (most were of the asymptotic type). However, over half of the delayed recruiters showed excursions larger than five db. Hirsh, Palva and Goodman (6) gave a critique of difference limen-recruitment relationship at near threshold levels, and

concluded that the Bekesy audiometer measures individual variability around threshold rather than difference limen or recruitment directly. This was supported by Landes (9) when he substituted a potentiomenter giving changes in loudness for the usual Bekesy audiometer attenuator giving linear db changes. He found increased concurrence between the presence of recruitment and decreased Bekesy-type audiogram excursions, and concluded that the Bekesy results are related to loudness change, not difference limen.

Differences among subjects in pattern or type of recruitment, rate of auditory adaptation (TTS), difference limen and/or variability around threshold all have been suggested as being related to differences in amplitude of excursions on the Bekesy audiogram. In addition, because increased attenuation rate results in increased amplitude (1, 2, 5) the factor of reaction time may play a role in determining amplitude of tracing. Such a reaction time factor was first suggested by Bekesy himself (1). That is, for a given attenuation rate the subject with the given reaction time would be expected to allow the attenuator to overshoot (either in the ascending or in the descending direction) by a given amount before pressing or releasing the control switch. A subject with a shorter reaction time would be expected to respond with less time delay to a given loudness sensation and, therefore, to demonstrate smaller excursions.

However, neither the relationship between reaction time nor difference limen size and width of tracing on the Bekesy audiogram has been studied directly. If range of excursion is to continue to be of interest when interpreting Bekesy audiograms, such factors as these need to be considered. The purpose of the present study was to investigate the relationships among reaction time to tones, difference limen for tones, and width of excursions on the pure tone Bekesy audiogram for normal hearing subjects.

## PROCEDURE

*Subjects.* The subjects were 21 white males, eleven white females and one female of Japanese-Hawaiian descent. All were between eighteen and thirty one years of age and all were students or secretarial employees at the Pennsylvania State University. None had known motor disability or history of such difficulty, and all had hearing adequate to pass a pure tone sweep check at 15 db for octave frequencies 250 through 4000 cps.

During experimental testing half of the subjects used their right ears and half used their left. The order of administering the three experimental tests was systematically rotated among consecutive subjects (1-2-3, 2-3-1, 3-1-2, 1-2-3, and so forth). Within each test procedure the order of presenting the three test tones was rotated in a like manner, but the order of

tones was not related to the order of test administration Each subject was given practice trials on each experimental test using a 500 cps tone immediately preceding the actual test run. Subjects were given the following experimental tests.

*Bekesy audiogram.* A Grason Stadler E-800 Bekesy-type audiometer was set for hearing loss calibration. Attenuation rate was nominally 2.5 db per second, but calibration of the audiometer indicated an actual rate of 2.3 db per second. Bekesy-type thresholds were obtained for one minute at each of the frequencies 250, 1000 and 4000 cps. Subjects were instructed to press the control switch as soon as they heard the tone, and to release the switch as soon as they could not hear the tone. The minute of testing time was begun after the first four reversals of the recording pen at each frequency. For each subject at each frequency tested the mean db range of the Bekesy tracing (after the first four reversals) was computed. Continuous tones were used.

*Reaction time.* Woodrow (21) indicated no significant difference in reaction time between the methods of pressing a switch or releasing a switch in response to a stimulus. Woodworth and Scholsberg (22) found that the more intense the stimulus the shorter the reaction time, and Telford (20) suggested that the shortest reaction time is obtained with a forewarning period of between one and two seconds. On the assumption that a technique which would minimize reaction time would tend to reveal differences among subjects, both forewarning and a comfortably loud tone (forty db above each subject's threshold) were utilized from the continuous output of a pure tone audiometer. A telegraph key was in series with a knife switch, the coil of a double relay, and a battery. The subject depressed the telegraph key on the command "Ready" to close the first section of the circuit to the relay. After a random delay of one to two seconds the experimentor closed the knife switch to operate the relay switch contacts. This completed the tone circuit to the earphone which the subject wore and the circuit to the timer which measured cumulative time in .01 second intervals. The subject was instructed to release the telegraph key when he heard the tone. This interrupted the tone and stopped the timer by means of the relay. Twenty trials were run at 250, 1000 and 4000 cps each. The time between trials was varied randomly from one to five seconds. The cumulative reaction time at each frequency was divided by twenty to obtain the subject's mean reaction time.

*Difference limen.* The difference limen procedure used was similar to that described by Luscher (12) and by Luscher and Zwislocki (13). The output of a clinical audiometer was fed to a relay automatically operating a

double pole-double throw switch at the rate of two cycles per second. In one position the switch allowed an unattenuated tone to pass, while the other position passed the tone signal through a potentiometer in a box controlled by the subject to give continuously variable attenuation. Testing was done at forty db above the subject's threshold for frequencies 250, 1000, and 4000 cps. Each subject was given four trials at each tone; two were from large difference between tone pulses, and two were from zero difference between tone pulses. Subjects were instructed to find the setting for just perceptible difference in tone pulses. A numerical scale at the bottom of the potentiometer was read after each trial; the mean reading was obtained and converted to the nearest 0.1 db.

## RESULTS AND DISCUSSION

Table 1 shows the mean, range and standard deviation of scores for each experimental test at each frequency. Inspection of Table 1 indicates that for the Bekesy and Difference Limen tests the mean values decreased as the frequency of test tone increased; however, mean reaction time was relatively stable. Comparisons among the mean, range, and standard deviation at each frequency strongly indicate skewed distributions for all three tests at all three frequencies. For example, the mean DL at 4000 cps was 0.49, which is only about one-fourth of the distance from the bottom of the range of scores. The standard deviation for DL at 4000 cps, being 0.56 (larger than the mean on an absolute db scale), also reflects this skewness.

It is also noticeable that for the Bekesy test the lower limits of the ranges of average excursion were well below the five db often considered to be indicative of recruitment. The standard deviations at the three frequencies, when subtracted from their respective means, give values of 3.13, 3.61 and 1.31 db for 250, 1000 and 4000 cps respectively. At 250 cps four subjects had excursion averages less than 3.13 db, at 1000 cps twelve subjects had excursion averages less than 3.61 db, and at 4000 cps one subject had an excursion average less than 1.31 db.

Table 2 shows the produce moment correlations for scores on pairs of experimental tests at each frequency. The only $r$ value significantly different from zero at the .05 level was for the Bekesy vs. Difference Limen at 250 cps. (For N34, $r$ .336 is required for significance at the .05 level.) The only other $r$ values which approached the .05 level were between Difference Limen and Reaction Time, but there is no rationale for these performances as measured in this study to be inter-related.

Table 1. Means, range of scores and standard deviations of experimental test scores (N 34).

| | Bekesy (db) | DL (db) | Reaction Time (seconds) |
|---|---|---|---|
| **Mean** | | | |
| 250 cps. | 6.78 | 1.36 | .19 |
| 1000 cps. | 5.47 | 0.69 | .20 |
| 4000 cps. | 5.18 | 0.49 | .20 |
| **Range** | | | |
| 250 cps. | 2.5-16.8 | 0.1-5.0 | .12-.48 |
| 1000 cps. | 1.7-14.9 | 0.1-2.8 | .11-.54 |
| 4000 cps. | 1.1-20.5 | 0.1-2.0 | .13-.45 |
| **Std. Deviation** | | | |
| 250 cps. | 3.65 | 1.15 | .07 |
| 1000 cps. | 2.86 | 0.66 | .08 |
| 4000 cps. | 3.87 | 0.56 | .07 |

Table 2. Product moment correlations among subject test scores (N 34).

| | frequency | | |
|---|---|---|---|
| | 250 | 1000 | 4000 |
| Bekesy vs. DL | +.38* | +.07 | +.18 |
| Bekesy vs. React. Time | -.12 | +.07 | +.05 |
| DL vs. React. Time | -.03 | +.27 | +.31 |

*Significant at .05

The data shown in Table 2 do not support the hypothesis of a relationship between reaction time and range of excursions on the Bekesy-type audiogram. This may be generalized to populations other than the normal hearing (namely, hearing defective) in whom the specific defect would not be presumed to cause other than normal amounts of variation in reaction time. In this study the attenuation rate utilized was fast in comparison to some rates used previously (for example 0.5 and one db per second). The E-800 Bekesy-type audiometer has available an attenuation rate of approximately six db per second. Whether or not a relationship exists between reaction time and excursion size for such an attenuation rate is not indicated by the present data. In the present Bekesy procedure the rate of change of loudness may have been so slow that differences in reaction time did not result in various amounts of attenuator "overshoot" such as would have been shown by a faster attenuation rate.

Although there was a significant correlation between excursion on the Bekesy audiogram and difference limen at 250 cps, the correlation was low and in terms of the coefficient of alienation (15) has the effect of reducing the random error of estimate about eight per cent; only a small portion of the variability between Bekesy excursions and difference limen is accounted for by the observed r at 250 cps. The correlation coefficients at the other two frequencies, being low and non-significant, do not support the hypothesis that Bekesy audiogram excursions are related to difference limen. (This conclusion rests upon the assumption that although DL near threshold may be different than DL at 40 db above threshold, there is a high degree of relationship in normals between DL at threshold and at forty db above threshold.)

## SUMMARY

Bekesy audiogram threshold tracings for one minute, reaction time to onset of tone, and difference limen at forty db sensation level were obtained for 34 normal subjects. Test tones were 250, 1000 and 4000 cps. Correlations among mean size of excursions on the Bekesy test, reaction time and size of difference limen were computed for each frequency tested. A low correlation (r.38) significant at .05 was found between Bekesy excursions and difference limen at 250 cps. All other correlations were not significant at the .05 level. It was concluded that among normals size of excursions on the Bekesy audiogram is not related to reaction time, nor to difference limen at the middle and upper audiometric frequencies.

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# AN EVALUATION OF THE REGER-NEWBY GROUP HEARING TEST ADMINISTERED MANUALLY

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## INTRODUCTION

While there are many group hearing tests (5) (6) (10) suitable for use with an adult population, concern has been expressed or implied (2) (11) relative to the lack of an adequate group procedure for public school use. In order to be acceptable for this purpose, a group hearing test must meet not only the basic criteria that transcend any such test, but also special criteria associated with the population for which it is designed or, in this case, certain features unique to the public school environment. Suggested below are several basic and special criteria which could be used for the evaluation of such a test. These criteria are admittedly arbitrary in some instances and not always mutually exclusive. Nevertheless, they are judged to be at least a rough index of the suitability of a screening test of hearing for group use in the public schools.

1. *Stimulus.* Since hearing acuity is usually associated with deviation from audiometric zero, procedures utilizing pure-tone audiometric techniques are considered most suitable.

2. *Validity.* A group test should identify a very high percentage, if not all, of medically significant hearing losses as defined by individual audiometry. Thus, the false-pass rate should be very low.

3. *Reliability.* Test-retest agreement should be very high for successive administrations of the procedure.

4. *Efficiency.* Test efficiency, as used here, is defined in terms of the false-fail and false-pass rates. To have a satisfactory level of efficiency, a test should identify the medically significant losses without rejecting an excessive number of children who have normal hearing. That is, the false-fail percentage should be low.

It can also be argued that any procedure that fails to recognize virtually all hearing losses is not very efficient. Accordingly, the false-pass percentage should also be very low.

5. *Time.* A test should permit the screening of school children as rapidly as possible while maintaining satisfactory validity and reliability. It is felt by

the writers that, for practical reasons, administration should permit evaluation of at least three groups of up to 40 children each hour.

6. *Equipment.* In general, existing equipment should be utilized. That is, since a pure-tone audiometer and multiple phones are available to many school systems, the procedure should be adapted to such equipment rather than devised in such a way as to necessitate the purchase of new and/or accessory items.

7. *Simplicity.* A test should be simple enough to allow satisfactory performance by first-and second-grade pupils. Moreover, since in many situations the procedure will be administered by persons other than trained audiologists, a test should be easy to understand, administer and score.

Of those screening procedures (1) (2) (4) (7) (8) currently available for use with school children, the pulse-tone technique would seem to exhibit the best potential of ultimately meeting all of the stated criteria. One commonly used pulse-tone procedure designed expressly for use in the public schools originated with Reger and Newby (10) and was evaluated on children by Newby (9). The procedure was not, however, a screening device and since it was the authors' intent to find or develop a group screening test of hearing suitable for public school use, it might seem unfair to evaluate the Reger-Newby procedure in these terms. Nevertheless, before attempting to develop a group screening test based on the pulse-tone technique, it would seem mandatory to re-evaluate the Reger-Newby approach. Moreover, the excellent reliability and validity reported by Newby suggests that the basic procedure is quite suitable for use with public school children. On the other hand, in order to administer the Reger-Newby test it is necessary to purchase and maintain special equipment. Thus, in its original form, the procedure is unable to satisfy the equipment criterion. In addition, there is some possibility that, because of test length and the semiautomatically controlled administration, the procedure may not meet the criterion of simplicity. However, if a modification of the Reger-Newby test could be shown to satisfy all of the stated criteria, there would be no necessity of embarking upon a series of studies designed to develop a related form. Moreover, it would seem that slight changes in the administration of the test might permit all criteria to be met. Thus, the basic procedure developed by Reger and Newby was modified by replacing the special automatic audiometer with a standard unit and test administration was carried out under manual control. All other aspects of the procedure were followed as rigourously as possible. The purpose of this study was to evaluate the resulting modified group hearing test and compare the results to those reported by Newby for the parent test.

## PROCEDURE

A slightly modified Reger-Newby group hearing test was evaluated with public school children as subjects. Except for the stated change, an attempt was made to replicate exactly the procedure as described by Newby (9). This included using the same instructions, test forms, sequence of db levels, retest procedures and so on. The test frequencies (256, 1024, 2048 and 4096 cps), however, were changed slightly for reasons listed below.

*Subjects.* Subjects were 495 school children drawn from the Waco, Texas public school system. Children from the third through sixth grades were obtained from two elementary schools and those in the seventh and eighth grades were obtained from the Physical Education and Health classes of a junior high school. These are the same age and grade ranges used by Newby and it was judged that the results generally should be comparable to his.

*Equipment.* Forty Permoflux PDR-1 earphones in MX cushions were connected through an impedance-matching device to the output of a Beltone 10-A audiometer. Each headset consisted of a single earphone attached to a plastic covered steel head band. A 100 watt yellow light bulb in a conical metal lamp shade was used as an "attention" light, specifically to replace a similar device incorporated in the Reger-Newby automatic audiometer. This unit was independent of the audiometer and controlled by a foot switch operated by the administrator. The switch was placed on the floor near the audiometer and the light was positioned so it could be easily seen by all members of the group being tested.

*Calibration of Equipment.* Since an artificial ear was unavailable, two calibration procedures were used. Ten female college students whose hearing was known to be within 5 db of audiometric zero made loudness balance judgments of the output of each earphone against a recently calibrated pure-tone audiometer by standard ABLB technique. This procedure was carried out at +20 db and at least twice for each of the 40 earphones at each of the test frequencies. Except for 256 cps the maximum deviation at any frequency for any phone was less than 5 db.

Comparable results were obtained with a second calibration procedure in which the 40 phones were used to obtain hearing thresholds for a group of five female college students with known thresholds. The procedures described indicated that the phones were satisfactorily calibrated at all test frequencies except one. For this frequency (256 cps) variation among the headphones was found to be excessive. Accordingly, the frequency of 500 cps was substituted. Calibration was satisfactory for 500 cps and it was judged that this substitution did not bias the results as it is generally accepted that any of

the frequencies from 125 to 500 cps are usually as representative of the group as any other.

*Administration.* The investigators attempted to duplicate Newby's presentation of randomly selected pulse groups. As expected, however, it was impossible to replicate exactly his time pattern of one second pulses separated by .5 second silence. A close approximation was made in the following manner: The administrator counted slowly to himself, "zero and one and two and three and four" with the entire sequence requiring approximately seven seconds. He did this for each group no matter how many pulses were actually presented. On the count of "zero" the foot pedal was pressed to illuminate the "attention" light; on the count of "one" the first pulse was presented; on the count of "two" the second pulse and so on. After the count of "four" the attention light was extinguished and, while subjects were marking their papers, the audiometer was adjusted to the next setting. This procedure was repeated until the last pulse group of a given series had been presented, after which the frequency and level adjustments were made for the next series and the entire procedure repeated. After completing the test on the right ear, the phones were reversed and the left ear was evaluated in the same manner.

*Retest Procedures.* In order to evaluate the validity of this procedure, an individual pure-tone test was administered to 178 of the subjects. This group was comprised of all who failed the first group test plus a randomly selected 10 percent of those who passed. The criterion for group-test failure was a loss of 20 db or more at at least one frequency for either ear. The individual pure-tone test, which was administered within three days of the group test, employed standard audiometric procedures with the exception that testing was terminated at the level of +5 db.

In order to evaluate test-retest reliability, the group procedure was readministered to all subjects exactly one week following the first test. For both group tests each subject was provided with the same earphone; the administration of the second procedure was identical with the first.

## RESULTS

*Measures of Reliability.* Table 1 presents test-retest reliability contrasted with the results reported by Newby. Values are in percent for all subjects who received both group tests. In the rows may be seen the data for the four test frequencies and in the columns, the differences in 5-db steps from group test to group retest. In evaluating the table, the major comparison to be made is between the two studies. For example, at 1000 cps, Newby reported that 85.5 percent of the ears he studied showed no difference from

group test to group retest whereas at the same frequency only 47.0 percent of the ears evaluated in this study showed no difference.

Comparison of the two sets of data will indicate that test-retest agreement for this study is poorer than that reported by Newby. For this investigation a smaller percent of children showed no difference for any frequency, whereas, for differences of 20 db or more, a much greater percentage was found than was reported by Newby.

Table 1. Test-retest reliability. Composite of percent of children's ears from third through eighth grades comparing differences (in db) from group test to group retest obtained from this study (N=970 ears) to those reported by Newby (9) (N=840 ears.

| Frequency in cps | Study | Differences in 5 db steps | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 |
| 500 (256) | Newby | 63.5 | 25.7 | 6.5 | 2.1 | 0.7 | 1.3 | 0.1 | 0.0 |
| | Present | 30.4 | 34.4 | 21.4 | 7.0 | 3.5 | 2.8 | 0.3 | 0.1 |
| 1000 | Newby | 85.5 | 8.8 | 3.8 | 1.5 | 0.0 | 0.2 | 0.0 | 0.1 |
| | Present | 47.0 | 25.4 | 16.4 | 5.6 | 2.3 | 2.7 | 0.3 | 0.2 |
| 2000 | Newby | 80.6 | 11.3 | 5.8 | 1.1 | 0.2 | 0.7 | 0.1 | 0.1 |
| | Present | 62.6 | 16.8 | 11.1 | 3.9 | 2.1 | 2.2 | 0.2 | 0.1 |
| 4000 | Newby | 83.6 | 10.6 | 3.5 | 0.5 | 0.5 | 0.6 | 0.1 | 0.7 |
| | Present | 65.6 | 13.6 | 10.4 | 4.3 | 2.0 | 3.0 | 0.3 | 0.8 |

Table 2 is a partial summation of Table 1 and presents accumulated differences at three levels allowing comparison between the two studies. In the rows are listed accumulated percentages of ears with differences of 15 db or less in the first double row, of 10 db or less in the second, and 5 db or less in the third. In the columns are listed these values for each of the frequencies. A comparison of the two sets of data reinforces the observed differences in test-retest reliability noted in Table 1. For example, at 4000 cps Newby's value at 5 db or less is the same as that for 15 db or less in this study. Moreover, as high as 35 percent (at 500 cps) of the ears tested in this study exhibit test-retest differences of at least 5 db. Although

this may be accounted for in part by actual threshold changes caused by a certain number of upper respiratory infections which were being experienced by this population, the basic reason is undoubtedly the inability of the subjects in this study to perform equally well on the two administrations of the modified test. Thus, it would seem that the modified version of the Reger-Newby test does not exhibit as satisfactory reliability as does the parent test.

Table 2. Comparison of percentages of ears showing differences of specific magnitudes from group test to group retest. Both the results of this study (N=970 ears) and those reported by Newby (9) (N=840 ears) are given.

| Difference | Study | Frequency in cps | | | |
|---|---|---|---|---|---|
| | | 500 (256) | 1000 | 2000 | 4000 |
| 15 db or less | Newby | 98 | 100 | 99 | 98 |
| | Present | 93 | 94 | 95 | 94 |
| 10 db or less | Newby | 96 | 98 | 98 | 98 |
| | Present | 86 | 89 | 92 | 90 |
| 5 db or less | Newby | 89 | 94 | 92 | 94 |
| | Present | 65 | 72 | 80 | 79 |

*Measures of Validity.* Table 3 is structured identically as Table 1 excepting that the percentages reported represent the differences between the first group test and the individual test. It is apparent that agreement between the group test and the individual test is much poorer for the modified test - especially at 500 and 1000 cps. At these frequencies Newby's data show considerably better agreement between the two tests. For example, at 256 cps, he reported that 79.7 percent of the observed differences were 5 db or less and only 4.8 percent were as great as 20 db. On the other hand, for the modified test, values as high as 15.7 percent (at 500 cps) were found for differences of 20 db and over.

Table 3. Measures of Validity. Composite of percent of children's ears from third through eighth grades comparing differences (in db) from group test to individual test obtained from this study (N=356 ears) to those reported by Newby (9). (N=188 ears).

| Frequency in cps | Study | Differences in 5 db steps | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 |
| 500 (256) | Newby | 55.8 | 23.9 | 9.6 | 5.9 | 2.7 | 1.6 | 0.0 | 0.5 |
| | Present | 22.2 | 29.5 | 23.0 | 9.6 | 3.9 | 10.1 | 0.6 | 1.1 |
| 1000 | Newby | 67.5 | 19.7 | 7.4 | 3.2 | 0.2 | 0.5 | 0.0 | 1.1 |
| | Present | 51.4 | 21.9 | 10.4 | 8.7 | 1.1 | 3.9 | 0.6 | 2.0 |
| 2000 | Newby | 61.2 | 25.0 | 6.9 | 3.2 | 2.1 | 0.5 | 0.0 | 1.1 |
| | Present | 63.2 | 14.0 | 10.1 | 5.0 | 1.4 | 3.9 | 0.0 | 2.2 |
| 4000 | Newby | 65.9 | 16.5 | 6.4 | 5.3 | 1.6 | 1.6 | 0.5 | 2.1 |
| | Present | 61.0 | 12.6 | 11.0 | 4.8 | 1.7 | 5.9 | 0.3 | 2.8 |

Table 4 is structured identically with Table 2 except the percentages shown are differences between the group and individual tests. Observation of the table will indicate that Newby's original test shows better validity in every instance. In fact, at 500 cps, the modified test had only 52 percent of the ears showing agreement of 5 db or less. At this same level, however, Newby reported a value of 80 percent.

Table 4. Comparison of percentage of ears showing differences of specific magnitudes from group test to individual test. Both the results of this study (N=356 ears) and those reported by Newby (9) (N=188 ears) are given.

| Difference | Study | Frequency in cps | | | |
|---|---|---|---|---|---|
| | | 500 (256) | 1000 | 2000 | 4000 |
| 15 db or less | Newby | 95 | 98 | 96 | 94 |
| | Present | 84 | 92 | 92 | 89 |
| 10 db or less | Newby | 89 | 95 | 93 | 89 |
| | Present | 75 | 84 | 87 | 85 |
| 5 db or less | Newby | 80 | 87 | 86 | 82 |
| | Present | 52 | 73 | 77 | 74 |

*Measures of Efficiency.* The efficiency of the modified test was investigated using two criteria of significant hearing loss. The first (criterion A) was a loss of 20 db or more at two or more frequencies, or a loss of 30 db at one frequency, in either ear. The second (criterion B) was a loss of 20 db or more at one frequency, in either ear. Table 5 presents these data and compares the results to those reported by Newby. In the rows are listed the percentage of ears with loss (or absence of loss) based on the two criteria for the group test. In the columns are the values for the individual test.

Table 5. A comparison of the efficiency of the test reported by Newby (9) (N=188 ears) to the modified procedure carried out in this study (N=356 ears) at two criteria of hearing loss. All values are percentages.

| Group Test | Significant loss (Criterion A*) | | No Significant loss | |
|---|---|---|---|---|
| | Newby | Present | Newby | Present |
| Significant loss (Criterion A*) | 6.4 | 9.3 | 11.2 | 27.5 |
| No significant loss | 5.3 | 4.5 | 77.2 | 58.7 |
| Significant loss (Criterion B**) | 10.1 | 11.0 | 18.6 | 40.2 |
| No significant loss | 1.6 | 2.8 | 69.7 | 46.1 |

**Criterion A is a 20db loss at two frequencies or a 30db loss at one frequency in either ear.*

***Criterion B is a 20db loss at one frequency in either ear.*

In evaluating Table 5, criterion A will be considered first. Based on individual audiometry, the original test correctly identified 83.6 percent of the ears (this value was obtained by summing the correct-fail (6.4) and correct-pass (77.2) percentages); the modified version 68.0 percent. Newby's false-fail rate was 11.2 percent, the rate for the present investigation was 27.5 percent. Thus, the modified version incorrectly failed over one quarter of the ears tested - proportionately more than twice the number reported by Newby. On the other hand, for this criterion the modified test shows a slightly better false-pass rate; that of 4.5 percent to 5.3 percent for the parent test.

For criterion B the difference between the two procedures is even more striking. The mechanically operated technique correctly identified 79.8 percent of the ears; the modified version only 57.1 percent. The false-fail rate was 18.6 percent for the parent test - proportionately well over twice that (40.2 percent) for the modified procedure. Evaluation of the false-pass percentages reveals that the Reger-Newby procedure missed only 1.6 percent of the medically significant hearing losses while the rate for the modified version was 2.8 percent. Thus, it would seem that the efficiency of the parent test, measured by the false-fail and false-pass rates, is generally superior to the modified version .

*Other Considerations.* Additional problems were found to occur with administrations of the modified procedure. First, mean test length was 32 minutes and hence, only about two groups per hour could be evaluated. Moreover, the actual administration of the test was found to be so demanding that even over short periods of time, administrator fatigue was experienced. This resulted in presentation errors.

Marking errors proved to be a problem and, even with assistance, some subjects exhibited difficulty in correctly recording their responses - especially during the early part of the test. Thus, it was necessary to have an assistant present in order to aid subjects in avoiding such errors. Moreover, a second assistant was necessary in order to correct test papers, which proved to be a time-consuming task. It is felt that it would have been impossible to conduct the test without the aid of these assistants.

## DISCUSSION

From the data presented above, it must be concluded that the original Reger-Newby group hearing test appears to be superior in most respects to the modified procedure. On the other hand, neither of these procedures are actually screening techn iques but rather are more nearly analogous to thresh old audiometry. In either form, the test is too long and cumbersome to permit simple and swift identification of hearing losses. A substantial modification in the direction of a simpler screening might be desirable. Moreover, the widespread use of the original test is impractical since the necessary special equipment is costly to obtain.

Accordingly, in order to meet the clearly established need for an adequate screening test of hearing, it is necessary to develop a test that would include some of the excellent features of the Reger-Newby approach but which would also involve major changes in procedure. Thus, the questions to be asked are: Which features should be retained, Which should be modified and, most important, What new features should be developed?

On the basis of this research and the author's experience with other group hearing tests, it is judged that in order to satisfy the criteria listed above, a group screening test of hearing should incorporate the following characteristics:

*1. Stimulus.* Newby (9) and others (3) have demonstrated the applicability of the pulse-tone or "spurt" stimulus with school age children. Therefore, it is suggested that this technique be utilized.

*2. Test Length.* A screening test should be long enough to permit valid identification of hearing losses and yet short enough so that the participants will not become excessively fatigued or bored.

A total of no fewer than 18 or greater than 48 frequency hearing level combinations would allow for satisfactory validity yet circumvent the undesirable effects. Since presentation of only two or three frequencies at cut-off levels of +15 or +20 db is generally accepted as adequate for individual sweep checks, it is suggested that such features be incorporated in the test.

*3. Presentation of Levels.* A descending series of four or five levels is considered desirable because it allows the child to become oriented to the signal before relatively faint levels of hearing are reached.

*4. Test Papers.* Proper marking by subjects of test responses has proved difficult with certain of the existing group hearing tests. Moreover, scoring of these responses is often found difficult and time-consuming. It is suggested that relatively simple answer sheets be designed; in fact, forms easy to use even by very young school children. Moreover, it is suggested that these answer sheets should allow for quick scoring by use of a template. For this purpose, it would seem appropriate to utilize a checkoff technique that allows choice of the correct response from all possible responses within a presentation.

*5. Practice Series.* Superior results are usually obtained for this type of a test if the task is clearly understood before the test itself is initiated. Accordingly, it is suggested that a practice series of three or four items in length be included.

*6. Visual Aids.* From the authors' experience with group hearing tests, it is apparent that superior performance is obtained when visual materials are used for instruction. Accordingly, it is suggested that such aids be included. A large replica of the answer sheet to which the children could be oriented prior to and during the test would be especially useful.

Of course, the above suggestions represent only one of the many possible approaches to the development of a vehicle designed to screen the hearing of children in large groups. However, the authors' judgment is that,

if these suggestions were incorporated into such a procedure, the resulting test would meet the design criteria specified here.

## SUMMARY AND CONCLUSIONS

A group pure-tone hearing test described by Newby, and altered to be presented manually, was administered to 495 subjects from the third through the eighth grades attending the Waco Public School System. In order to assess reliability, comparison was made of the results of two administrations of the group procedure; validity was investigated by comparing the results of the first group test to an individual test administered to 178 subjects, and efficiency was evaluated by means of the false-fail and false-pass rates. The results were compared to those reported by Newby for the original mechanically operated version of the test.

Comparison of the two procedures revealed that the parent test was superior in several respects .The original Reger-Newby procedure exhibited better group test-group retest and group test-individual test agreement than did the modified procedure; however, both were similar with respect to the false-pass rate. The parent test had a considerably lower false-fail rate, was much less fatiguing to the administrator, and required less time to administer. Therefore, it must be concluded that simple modification of the Reger-Newby group hearing test results in a considerably less effective vehicle. It is further concluded that this specific procedure is not suitable for modification to a group screening test of hearing and that an entirely new but somewhat related test should be developed. It is suggested that the new test should incorporate: 1. the pulse-tone or spurt stimulus, 2. a descending series of hearing levels, 3. from 18-48 pulse-tone sequences, 4. testing levels no lower than +20 or +15 db, 5. only two or three test frequencies, 6. test papers that are simple enough to use with primary school age children, 7. test papers that allow the use of templates for easy scoring, 8. a practice series of presentations, and 9. visual aids to allow for easy orientation to the task. Research is well advanced on a group screening test of hearing that incorporates these suggestions.

## ACKNOWLEDGMENT

*The authors wish to express their thanks for assistance extended by the Waco Public Schools, the Texas Department of Public Health, Dr. James F. Curtis and Dr. J. Donald Harris.*

*This paper, while reporting largely negative results, is presented here to save others the labor of traversing the same ground. A second paper, shortly to appear, will present a system of group audiometry for school children which does meet acceptable criteria of economy and validity.*

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# PROLONGATION OF THE ACTION OF THE ACOUSTIC REFLEX

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## INTRODUCTION

A review of the literature indicates that acoustic reflex (AR) contractions can be maintained for relatively long periods of time (1, 2, 3). However, recent efforts (4) to utilize the AR contraction as a protective mechanism against continuous noise were unsuccessful. Closer examination of the literature and of the details of the unsuccessful attempt suggested that the method of eliciting the AR contraction might have been the reason for failure.

Since the unsuccessful attempt to reduce temporary threshold shifts (TTS) resulting from exposure to continuous noise by use of the AR response, research has been completed which shows that decrease in AR response over time (adaptation) is most rapid for pure tones, less so for narrow band noise (NBN) and does not occur when clicks are used as AR arousal stimuli (5). Obviously, with continuous noise AR adaptation to the eliciting stimulus could be an important factor in reduction of TTS. The NBN and click AR stimuli also resulted in significantly larger contralateral threshold shifts (TS) than those from pure tones.

In view of the fact that more effective AR arousing and prolonging stimuli have been found, it was decided to conduct another experiment with more effective sounds to test whether they would provide reduction in TTS following exposure to continuous noise. The objective of this study, then, was to compare the effectiveness of clicks and NBN AR stimuli in reducing the TTS of Ss exposed to continuous noise.

## METHOD, APPARATUS AND SUBJECTS

A block diagram of the apparatus used in this experiment is presented in Fig. 1. The AR eliciting stimuli were clicks or NBN at 110 db SL. Clicks were programmed at 15/sec with a duty cycle of 10%. The NBN cut-off values, was determined by the Krohn-Hite filter, were 2000 and 2200 cps with a slope of 48 db/octave. The seven experimental conditions investigated in this study are presented in Table 1. Shown in the table are the stimuli presented to each of the S's ears, the level of stimulation for each sound used, and the ear from which the pre- and post-exposure thresholds were taken. Conditions 1 through 4 were designed to determine the

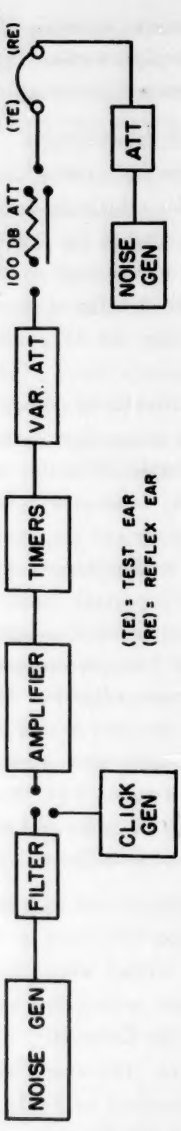


Figure 1. Block diagram of the apparatus used.

Table 1

The Seven Experimental Conditions

| | Stimulus in Test Ear | Stimulus in Reflex Ear | Ear in which pre- and post-exposure threshold, 4KC, taken |
|---|---|---|---|
| 1 | 110 db SL click | None | RE |
| 2 | 110 db SL NBN | None | RE |
| 3 | 110 db SL click | 110 db SPL white noise | RE |
| 4 | 110 db SL NBN | 110 db SPL white noise | RE |
| 5 | 110 db SPL white noise | 110 db SL click | TE |
| 6 | 110 db SPL white noise | 110 db SL NBN | TE |
| 7 | 110 db SPL white noise | None | TE |

TTS in the reflex ear resulting from stimulation by the AR arousal sound, with or without stimulation of the opposite ear. This information enables us to judge the relative noxiousness, if any, of the arousal sounds themselves when presented for prolonged periods of time. Conditions 5 and 6 were to determine whether reduction in TTS occurred when the AR was elicited and prolonged simultaneously with continuous noise exposure. The reference for these two conditions was provided by Condition 7, a primary control condition, which involved 110 db SP white noise in the test ear and no stimulation in the reflex ear.

Procedure in each experimental session entailed the determination of the 110 db SL for clicks or NBN for each S. Exposure to one of the experimental conditions followed immediately upon the determination of the pre-exposure threshold for the 4000 cps tone in either the reflex ear or the test ear. Upon completion of exposure the post-exposure threshold was determined. One experimental condition was presented per session. Duration of a session for each condition was 25 min. No S was scheduled more often than once per day.

The fourteen Ss serving in this experiment were staff members of the Psychology Division, ranging in age from 20-36. No screening was done for hearing deficit. A Latin square design was used to minimize possible order effects. Data were taken in the USAMRL mobile laboratory with an average ambient noise level of 35 db.

## RESULTS

Mean TTS's for each experimental condition are shown in Table 2.

Table 2

Table of Mean TTS for the Seven Experimental Conditions

| | Experimental Condition | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 5 | 6 | 7 | 3 | 4 |
| Mean TTS (in db) | 1.0 | -.43 | 28.42 | 28.14 | 39.28 | 11.35 | 7.85 |
| $\sigma$ | 8.5 | 10.8 | 11.3 | 15.0 | 14.5 | 16.4 | 10.0 |

The data were first subjected to an analysis of variance which revealed a significant difference among conditions significant beyond the .001 level of confidence. A t-test was then made to determine the significance of the differences between the TTS for condition 7 (the main control) and conditions 5 and 6 (the click and NBN conditions). The differences were significant beyond the 5% level of confidence. The clicks and NBN stimuli did not differ significantly one from the other in reducing TTS in the contralateral ear.

## DISCUSSION

These results strongly suggest that AR action was prolonged and was responsible for the approximately 11 db reduction in TTS found between conditions 5 and 6 and condition 7. If the AR contraction was responsible for the reduction in TTS noted in this experiment, then the contraction must have persisted for some time after the beginning of exposure to the noise. The data in no way permit one to infer how long the contraction was maintained. Evaluation of the practical importance of these results awaits further research.

It is of interest to note that TTS resulting from exposure to the AR eliciting stimuli was quite small in conditions 1 and 2, where no stimulation was given the opposite ear. On the other hand, TTS was considerably larger for conditions 3 and 4 where the opposite ear was exposed to 110 db SPL white noise. This would seem to suggest fatigue of the reflex for conditions 3 and 4 by virtue of exposure to the noise in the contralateral ear, with no fatigue (and therefore less TTS) resulting when the opposite ear was unstimulated.

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# CLINICAL OBSERVATIONS OF DIHYDRODESOXYSTREPTOMYCIN OTOTOXICITY

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ROGER S. MITCHELL, M.D., DENVER

## INTRODUCTION

The potential ototoxicity of the streptomycin group of antibiotics is well recognized. By means of clinical observation and animal experimentation, the toxicity of these drugs has been analyzed and described in detail, although according to Hawkins (3) further clarification of the location of the lesion in man is still needed.

In 1956, a new reduction product of streptomycin was developed by Ikeda and his associates (5, 6) at the Scientific Research Institute in Tokyo. Their studies with this chemical analogue of streptomycin, namely dihydrodesoxystreptomycin, suggested that it was as active or slightly more active than the parent compound. Consequently, in the search for an effective and non-ototoxic streptomycin drug, dihydrodesoxystreptomycin (DDSM) was made available to the Webb Institute for Medical Research* for study through clinical trial.

## MATERIALS AND METHODS

The study was designed to evaluate clinically the possible ototoxicity of DDSM. Also, renal function and retention of the drug in the blood were studied. Between June, 1959 and May, 1960, ten patients, hospitalized at Denver General Hospital with pulmonary tuberculosis, were selected to participate in the study. The patients consisted of eight men and two women, ranging in age from 29 to 67 years.

The patients below 55 years of age were given 1.0 gram of DDSM daily; those 55 and over received 0.5 daily. It was planned to give the drug for six months along with Isoniazid (INH) and Paraaminosalicylic acid (PAS), which are standard and non-ototoxic drugs used in the treatment of tuberculosis. Baseline audiograms were obtained prior to the start of DDSM chemotherapy on seven patients. In the other three patients, baseline audio-

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metric data were obtained very shortly after the start of treatment. Audiometric tests were repeated at two-week intervals during the course of treatment on all patients, and whenever possible, after the drug was discontinued. Testing was conducted in a sound treated two-room suite. Pure-tone thresholds for air and bone conducted stimuli were obtained at octave intervals from 125 to 8000 cps and the half octaves of 3000 and 6000 cps. Ascending thresholds were obtained using the modified Hughson-Westlake procedure described by Carhart and Jerger (1). Calibration of audiometric equipment consisted of measuring acoustic output of the test phones with an artificial ear and complimentary equipment. Calibration was checked at monthly intervals and maintained throughout the study. The audiometer's bone conduction system was calibrated following the procedures advocated by Roach and Carhart (8). Appropriate calibration corrections for air and bone conduction were applied to the audiometer's attenuator when necessary.

Cold caloric tests were administered to assess vestibular involvement.

Renal function was determined by blood urea nitrogen (BUN) and by creatinen clearance tests. Serum concentrations of DDSM were determined by bioassay.

## RESULTS

Four patients did not show changes in hearing during the time DDSM was being administered. These patients ranged in age from 29 to 67 years and the total dose of DDSM administered to them ranged from 58 to 94 grams. In three of these patients, it was not possible to continue audiometric tests after DDSM was discontinued. In one patient, however, pure-tone thresholds were recorded 75 days after DDSM was discontinued with no apparent shift in hearing up to that time .

The remaining six patients developed threshold shifts while being given DDSM or after the drug was discontinued. In the case reports of these patients which follow, audiograms do not include bone conduction thresholds. In all instances, bone conduction thresholds were measured on baseline audiograms as well as on subsequent tests whenever the air conduction thresholds showed a shift from the baseline levels. Since air and bone conduction curves were always superimposed, only the air conduction thresholds are reported.

*Case 1* (fig. 1). Mr. A. C., (DGH No.013542, age 57, received 1.0 gram of DDSM daily for 215 days from June 30, 1959 to January 31, 1960. This patient's baseline audiogram (fig. 1a) was obtained 24 days after the start of DDSM treatment. At that time, he had a mild, bilateral sensori-

neural hearing loss with slightly greater loss in the left ear for frequencies above 2000 cps. After 157 grams of DDSM, hearing in the right ear at 6000 and 8000 cps began to shift downward continuing gradually for the next 58 days. DDSM therapy was then discontinued and a final audiogram (fig. 1b) was obtained just prior to the patient's discharge from the hospital. At that time, the patient had suffered a 30 db shift in hearing in the right ear at 6000 cps and a 15 db change at 8000 cps. Thresholds in the left ear remained unchanged from the baseline levels during the 215-day treatment period. Follow-up audiometric study was not possible after DDSM medication was suspended. During DDSM administration, BUN remained within normal limits; creatinen clearance ranged between 66 and 104 cc/min.*

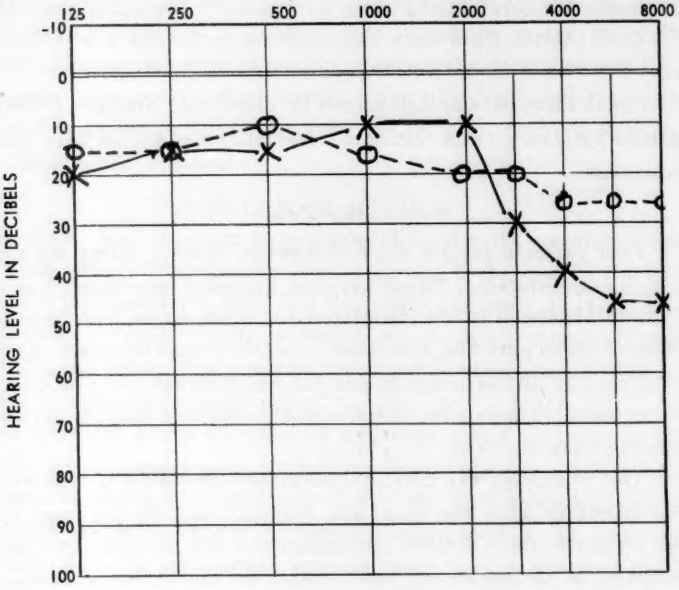


Figure 1a. Baseline audiogram.

*Normal in our laboratories is 50 cc/min or above.*

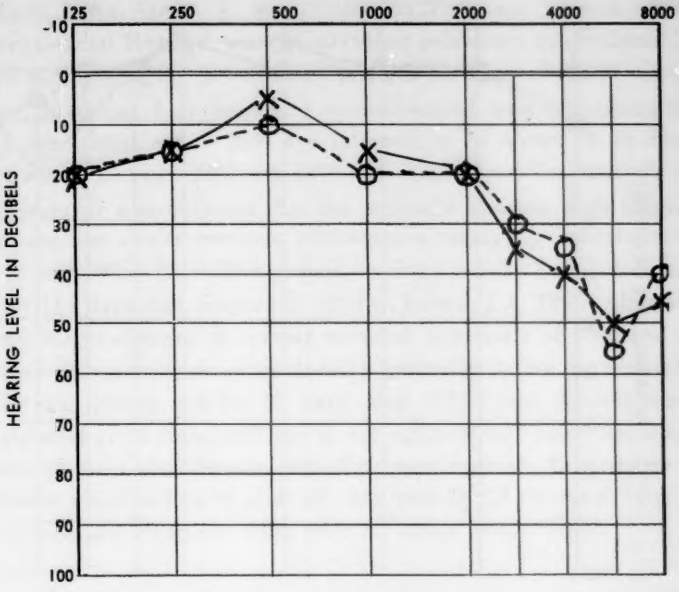


Figure 1b. Final audiogram obtained after 215 grams of DDSM.

*Case 2* (fig. 2). Miss D. H., (DGH No.019546), age 37, was admitted to the hospital with very far advanced bilateral tuberculosis. She received 1.0 gram of DDSM daily for 180 days, from August 1, 1959 to January 28, 1960. The patient's baseline audiogram (fig. 2a) was obtained six days after treatment with DDSM began. At that time, she had normal hearing bilaterally except for a 20 db sensori-neural notch at 6000 cps in the left ear. The patient's hearing remained unchanged during the 180 days DDSM was being administered and for three months after the drug had been discontinued. However, on the 93rd day after treatment with DDSM, a shift in hearing was observed in the right ear at 6000 and 8000 cps, which was still present 119 days after completion of treatment (fig. 2b). Hearing in the left ear did not change during or following DDSM treatment. The patient was not available for further audiometric tests beyond 119 days after completion of DDSM treatment. DDSM serum bioassay concentrations were 50 meg/ml at two hours and zero at 12 and 24 hours following the seventh 1 gram dose on August 7, 1959. BUN remained within normal limits throughout DDSM administration; creatinin clearances ranged between 41 and 91 cc/min.

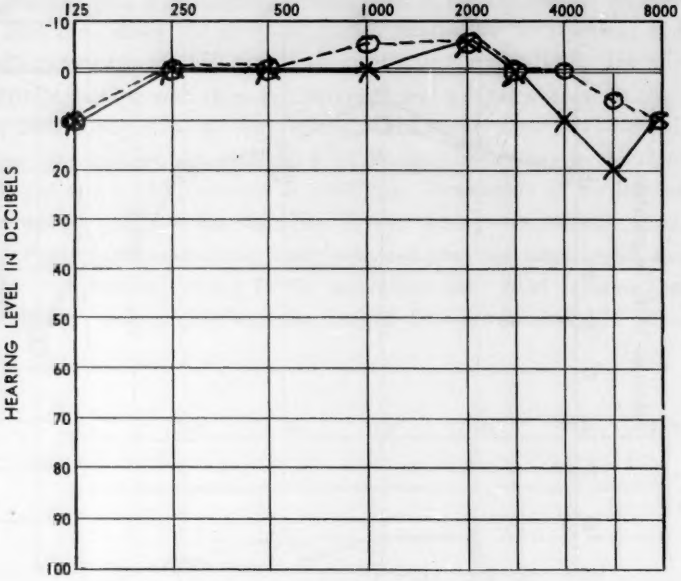


Figure 2a. Baseline audiogram.

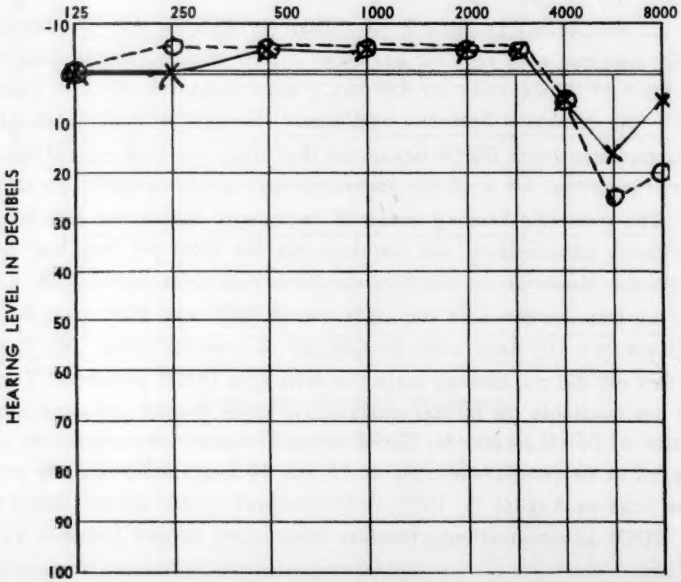


Figure 2b. Final audiogram obtained 119 days after completion of DDSM therapy.

*Case* 3 (fig. 3). Mr. R. E., (DGH No.012794), age 51, was admitted to Denver General Hospital with far advanced pulmonary tuberculosis. His baseline audiogram (fig. 3a) obtained prior to the start of DDSM revealed a severe, bilateral, high frequency sensori-neural type of hearing loss. Hearing was normal out to 2000 cps followed by an abrupt 70 db drop in the 1½ octaves between 2000 and 6000 cps range. From the patient's previous history, it was believed that the patient's baseline high frequency hearing loss was due to previous streptomycin therapy for tuberculosis in 1951 - 52 and 1956 - 57. This patient received a daily 1.0 gram dose of DDSM for 185 days from August 3, 1959 to February 4, 1960. After about 40 grams, slight changes in hearing occurred bilaterally at 3000 and 4000 cps. These changes continued to develop gradually during the remainder of the treatment period and for 85 days after DDSM was discontinued. A threshold shift of 15 db at 2000 cps in the right ear was first noticed audiometrically 57 days after therapy with DDSM was stopped. This patient was not followed audiometrically after 85 days post-DDSM treatment (fig. 3b). BUN and creatinin clearance tests were all within normal limits.

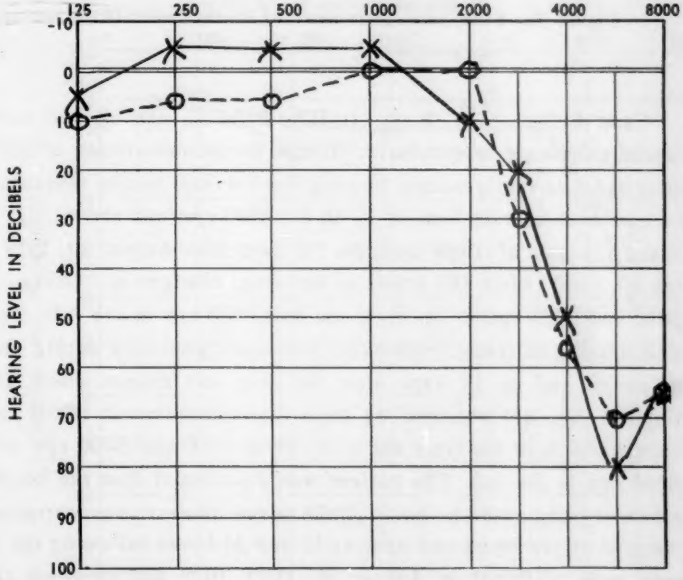


Figure 3a. Baseline audiogram.

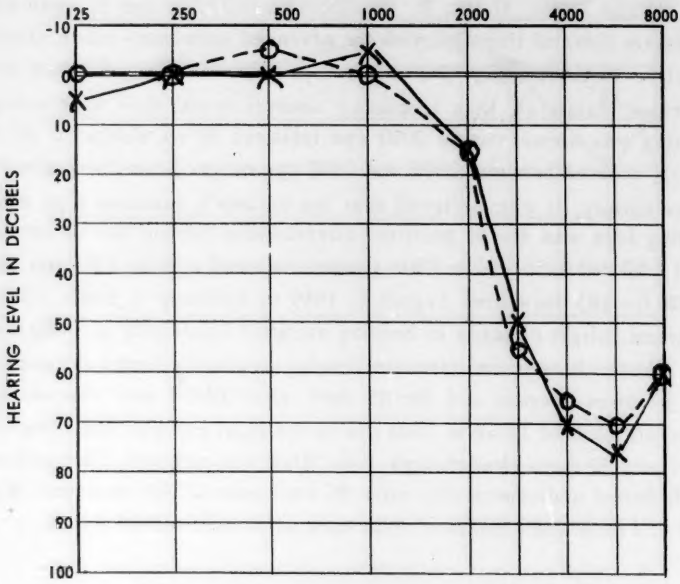


Figure 3b. Final audiogram obtained 85 days after DDSM therapy was permanently discontinued.

*Case 4* (fig. 4). Mr. M. S., (DGH No.013472), age 49, had moderately advanced pulmonary tuberculosis. Prior to the administration of DDSM, this patient had bilaterally normal hearing for low and middle frequencies and and a maximum hearing loss of 20 db for 4000 cps and above (fig. 4a). He received 1.0 gram of DDSM daily for 210 days from August 20, 1959 through March 17, 1960 . After 169 grams of the drug, changes in hearing occurred at 6000 and 8000 cps in the right ear and 8000 cps in the left. Deterioration of hearing at these frequencies continued gradually during the treatment period and for 14 days after the drug was discontinued. The last audiogram (fig. 4b) obtained 14 days after cessation of DDSM revealed threshold shifts in the right ear of 25 db at 6000 and 8000 cps and 35 db at 8000 cps in the left. The patient was discharged from the hospital before further tests could be made. DDSM serum bioassay concentrations were 25 meg/ml at two hours and zero at 12 and 24 hours following the seventh 1 gram dose of DDSM on August 26, 1959. BUN and creatinin clearance tests were repeatedly within normal limits.

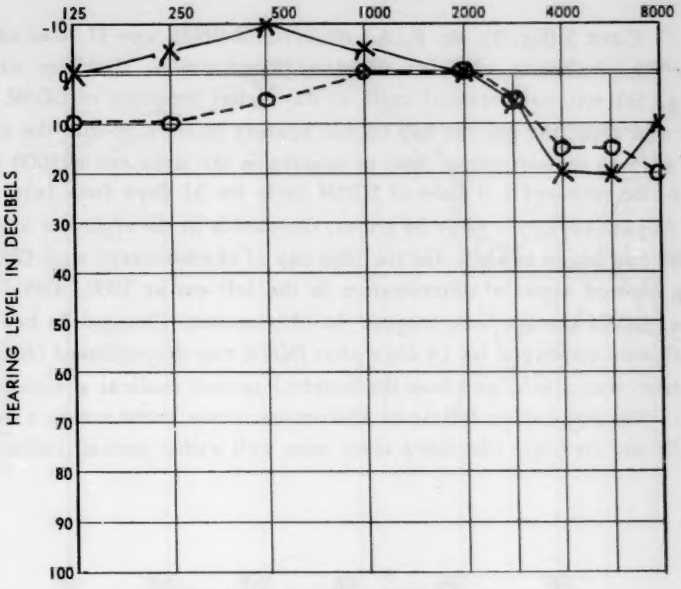


Figure 4a. Baseline audiogram.

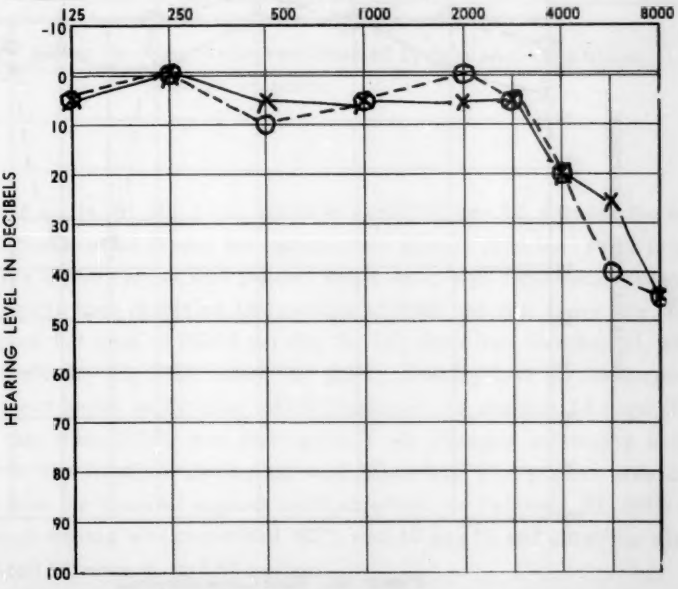


Figure 4b. Final audiogram obtained 14 days after DDSM therapy was permanently discontinued .

*Case* 5 (fig. 5). Mr. F. A., (DGH No. 014992), age 37, was admitted to the hospital with very far advanced tuberculosis. Baseline audiometry (fig. 5a) was not obtained until 10 days after the start of DDSM therapy. At that time, the patient had normal hearing bilaterally with the exception of a 45 db sensori-neural loss of hearing in the right ear at 3000 and 4000 cps. He received 1.0 gram of DDSM daily for 31 days from July 14, 1959 to August 14, 1959. After 24 grams, thresholds in the right ear at 6000 and 8000 cps began to shift. On the 30th day of chemotherapy with DDSM, hearing showed signs of deterioration in the left ear at 3000, 4000 and 6000 cps. DDSM therapy was stopped for this reason. Changes in hearing for both ears continued for 14 days after DDSM was discontinued (fig. 5b). The patient was discharged from the hospital against medical advice on August 31, 1959 and further follow-up audiometric tests could not be carried out. BUN and creatinin clearance tests were well within normal limits.

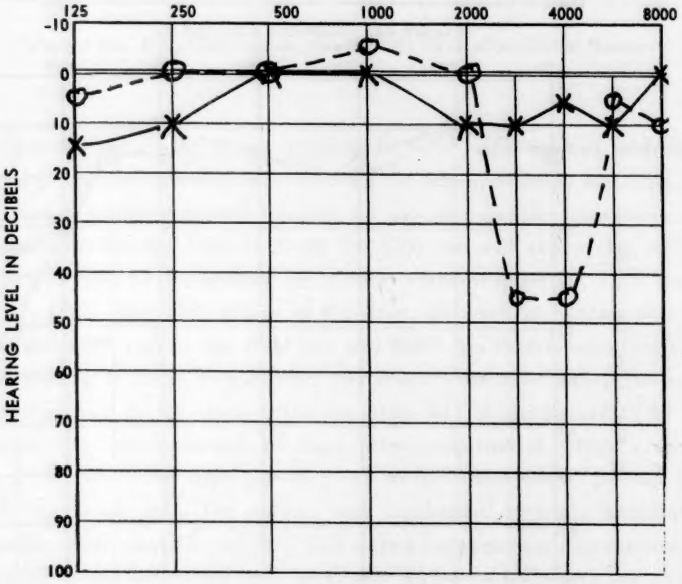


**Figure 5a. Baseline audiogram.**

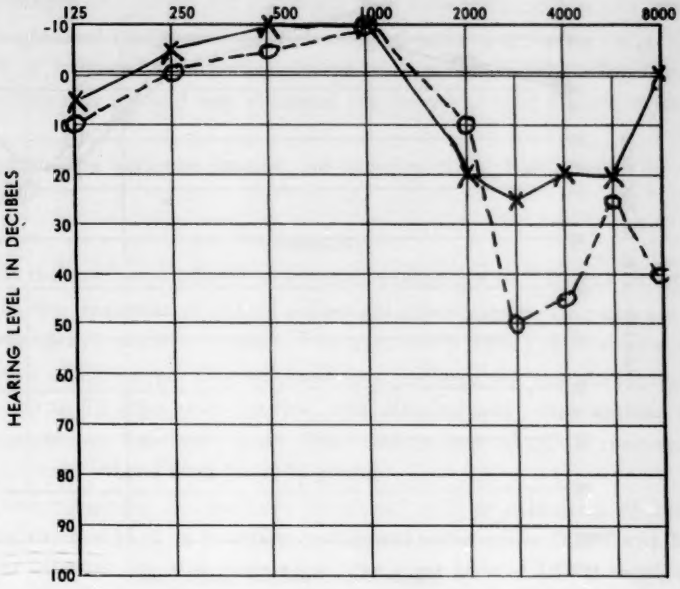


Figure 5b. Final audiogram obtained 14 days after completion of DDSM treatment.

*Case* 6 (fig. 6). Mr. J. A., (DGH No.009235), age 27, entered the hospital for treatment of severe left tuberculous pleural effusion. Prior to the start of the DDSM regime this patient had a mild, high frequency, sensorineural hearing loss involving frequencies of 3000 cps and above (fig. 6a). He received 1.0 gram of DDSM per day for 121 days from October 21, 1959 through February 10, 1960. After 107 grams, hearing loss for 8000 cps in the right ear began to develop which continued for another 14 days (fig. 6b). At that time, DDSM was discontinued. No changes in hearing in the left ear re the baseline audiogram were observed. The patient was discharged from the hospital against medical advice on February 20, 1960 and audiometric testing was concluded. BUN was 10 and 13 and creatinin clearance ranged between 41 and 63 cc/min.

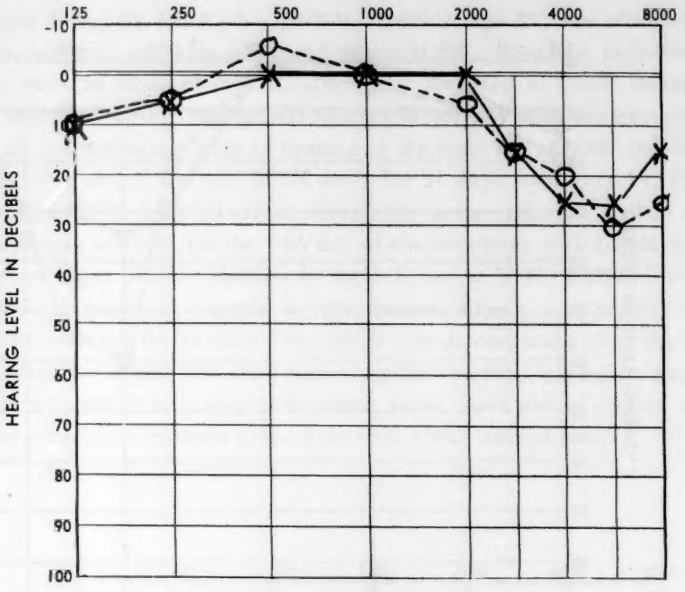


Figure 6a. Baseline audiogram.

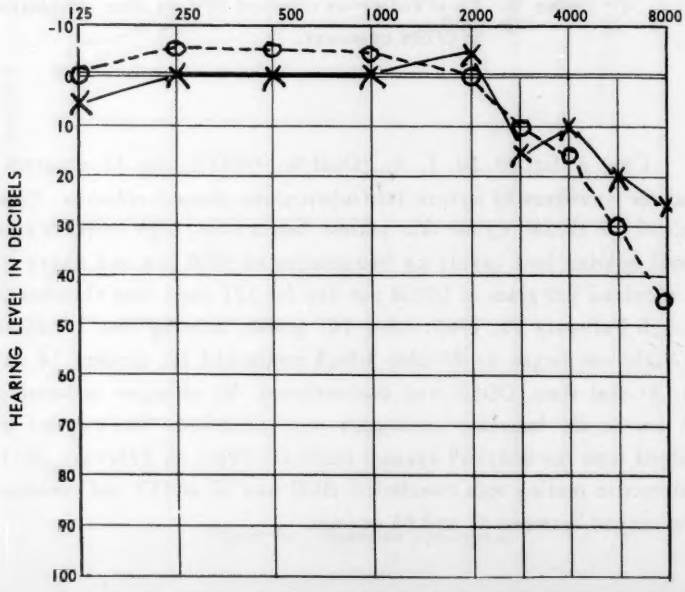


Figure 6b. Final audiogram obtained after 121 grams of DDSM.

Vestibular toxicity was noted in only two patients. One of those in whom changes in hearing did not occur had some dizziness which abated after the dose of DDSM was reduced from 1.0 gram to 0.5 gram daily. Case 5 (Mr. R. E.) showed a temporary change in response to cold caloric tests. No other patient showed any abnormal responses to cold caloric stimulation.

In the ten patients studied, no toxicity other than ototoxicity was observed.

## COMMENTS

Of the ten hospitalized patients receiving 0.5 to 1.0 gram of DDSM daily for the treatment of active pulmonary tuberculosis, four did not develop changes in auditory threshold for pure-tones during the time the drug was being administered. One of these four patients did not show ototoxic effects up to 75 days after the drug was discontinued; observations were not available in the other three. The total amount of DDSM received by these patients ranged from 58 to 94 grams.

The remaining six patients developed mild deterioration of hearing (not in excess of 35 db re baseline audiogram) either while DDSM was being given or after its use was suspended. The total dose of DDSM received by these patients ranged from 31 to 215 grams, and the amount of DDSM received at the onset of auditory disturbances, ranged from 24 to 180 grams. The changes in hearing involved only frequencies above 2000 cps and were most commonly confined to the region of 6000 and 8000 cps. None of the patients were aware of changes in hearing.

Audiometric data were obtained on four of the six patients with hearing loss during therapy after use of the drug was discontinued. One patient developed first signs of hearing loss 93 days after DDSM was removed from the therapeutic regime. In the other three patients, threshold shifts, which began while DDSM was being administered, continued to increase after use of the drug was stopped.

In three patients, elevated thresholds occurred only in the right ear and in one patient, changes in hearing involved the right ear initially and then the left ear after a time interval of six days. While it has been demonstrated time and again that hearing loss resulting from ototoxic drugs is strikingly bilateral, several isolated cases of unilateral involvement of the right ear have been reported. Naunton and Ward (7) report a case in which the hearing in the right ear diminished after 14 grams of streptomycin therapy. Christensen and his associates (2) found one case in which only the right ear was involved after 90 grams of DDSM. Similarly, Hawkins

(4) presents audiograms of a case in which Kanamycin was used for treating a tuberculosis patient. The patient had essentially normal baseline hearing and after 82 grams of Kanamycin, the right ear developed as much as 25 db loss of hearing at 4000 and 8000 cps. After 142 grams, the left ear also deteriorated in the high frequencies, however, to a greater severity of loss than the right ear.

While only few cases have been reported here, the data available suggest at least two provocative hypotheses; one, that in some individuals a difference between ears may exist in their susceptibility to ototoxic drugs, and two, perhaps, as in the case reported by Hawkins and the one found in the present study (5), the two ears do not show simultaneous ototoxic effects and that the behavior is observed best only when frequent audiometric measures are obtained.

Assuming that the observed changes in hearing would not have occurred if DDSM had not been given, this limited sample of clinical observations has shown that DDSM is not free of ototoxic agents and that the primary site of ototoxic disturbance is located in the auditory mechanism of the inner ear.

Renal function, as measured by creatinin clearance, was mildly abnormal in two cases (2 and 6) and normal in all others. Excessive retention of DDSM, as determined by serum bioassay concentrations was not observed. No relationship between renal function impairment, abnormal retention of DDSM and DDSM ototoxicity could be demonstrated.

## SUMMARY

1. Dihydrodesoxystreptomycin was given to ten patients with pulmonary tuberculosis in an effort to assess its ototoxicity.

2. Dihydrodesoxystreptomycin caused subclinical hearing loss demonstrated by audiometry in six of the ten patients, and the loss progressed after discontinuing the drug in the four patients so studied.

3. The hearing loss first appeared after 24 to 180 grams of the drug.

4. No significant dihydrodesoxystreptomycin vestibular toxicity was observed.

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# CHARACTERISTICS OF HEARING LOSSES PRODUCED BY GUNFIRE AND BY STEADY NOISE*

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## ABSTRACT

Various characteristics of permanent high-frequency tonal gaps produced primarily by gunfire in one group of men and by steady noise in another were compared, in order to determine whether or not subtle differences existed. No differences were found in slope of the audiogram near the gap, incidence of abnormal Albrecht effect (tone decay), or recruitment indices. The only significant difference found was in speech intelligibility score, and this is probably attributable to educational differences between the groups. General characteristics of the losses studied include these: (1) just below a tonal gap, a narrow region of increased sensitivity is often found; (2) recruitment functions are indistinguishable from those obtained in patients with Meniere's disease, and imply that recruitment is, on the average, complete at 100 db SPL; (3) although certain consonants heard in isolation may be confused by these men whose ears have 60- to 70-db losses at 3000 cps and above, very little loss in speech perception will be found until lower frequencies are also involved.

It has long been believed that there may be differences between the end-organ lesions produced by steady noise and those produced by single exposures to impulsive acoustic stimuli. The most recent statement of this point of view has been presented by Schuknecht and Tonndorf (12). After discussing the problem of high frequency hearing losses that are sometimes observed as a side effect of ear surgery, they proceed to treat the subject of acoustic trauma in general. Pointing out that the typical audiogram resulting from acoustic trauma (whether from gunfire, explosions, or headblows) is a tonal gap with a maximum in the neighborhood of 4000 cps, and that this corresponds to a localized cochlear lesion 8-12 mm from the oval window, they continue: "Such lesions are characteristically produced by acoustic transients (or by their bone-conducted equivalents) of rather high peak intensities. This is in contrast to a so-called noise trauma which

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results from prolonged and repeated exposure to noise, usually of lesser intensities. The salient point is that whereas a noise trauma is most likely the outcome of a slowly accumulating exhaustion on the cytochemical or enzymatic level without gross tissue destruction, acoustic trauma is the product of a *physical* injury involving local tissue lesions. Admittedly, much of what is finally seen histologically as the result of acoustic trauma is due to tissue degeneration *after* the injury; however, this is irrelevant from the present viewpoint and serves only to illustrate the apparent poor ability toward self-repair of the organ of Corti." (12, p. 496).

This hypothetical difference between "noise trauma" and "acoustic trauma" has been with us so long that there is apparently more than negligible danger that it may be accepted as fact. However, if one can ignore its disarming reasonableness, one finds that there is actually little in the way of experimental support for the notion. As far as we know, no one has ever presented compelling evidence of histological differences. And from our own studies of industrial hearing loss from steady and from impulsive noises, it has become apparent that pure-tone thresholds are often very similar in the two cases. In a recent article, for example, we showed three examples of hearing loss having nearly identical thresholds, but which had been caused by (1) a single firecracker, (2) repeated exposure to gunfire, and (3) habitual exposure to steady industrial noise, respectively (16).

However, we will be the first to admit that the isolated case rarely proves a point. It may still be true that *on the average* the losses from single impulsive acoustic stimuli may differ in some way from those produced over a period of months or years by steady noises with ordinary peak factors.

The practical significance that such differences would have is obvious, in view of the increasing number of compensation claims for loss of hearing. There is little doubt in our minds that many employers have been required to pay for a hearing loss incurred while the worker was shooting deer or skeet. Conversely, it is not unlikely that some of the veterans receiving compensation for hearing loss allegedly caused by gunfire during the war actually suffered the loss while working in the shipyards before the draft caught them. These inequities are caused by the fact that compensation boards (and, unfortunately, many otologists) generally take the position that if the man has been in a situation that has produced hearing loss in *anyone*, then that situation is assumed to have produced *his* loss. If there were indeed some significant differences between noise-induced and gunfire-induced losses, a more just assignment of liability could be made.

Ideally, a study to determine whether or not such differences exist should be experimental. That is, humans with known normal hearing should be exposed to specific steady and impulsive noises, and all aspects of the resulting hearing losses carefully measured. The next best (and more practicable) approach would be to expose other organisms in this way. We hope that such studies will be undertaken. However, a certain amount of indicative information can be extracted from survey-type data, provided that one remains aware of the limitations of this information. (Clearly, one can never be completely sure of the cause of an existing hearing loss if there is no record of the status of his hearing before and after the incident or period in question. A hearing loss that is attributed to noise may actually have been caused by an explosion, a blow on the head, or perhaps a childhood disease.)

However, suppose one has one group of men who have been exposed to gunfire for many years but who have never worked in steady noise, and another group who, although employed in high-level noise, have been exposed to only a minimum amount of gunfire. Even though *some* of the high-frequency losses found in the two groups may be due to head blows and disease, it is reasonable to assume that most of the losses were produced by gunfire in the first group, by steady noise in the second. In other words, although one would not expect all men in the primarily-gunfire (G) group to differ from all men in the primarily-noise (N) group, the average results should differ, if indeed the characteristics of noise-induced loss differ from those caused by gunfire.

Two such groups of men, all of whom had been given audiograms using ordinary octave audiometry, became available for intensive testing in 1959, so it was decided to compare some characteristics of their hearing. Since neither group could be considered a true random sample of "all men exposed to gunfire" or "all men exposed to steady noise," no useful generalizations could be derived from a comparison of average HLs of the two groups. Instead, it was decided to select and test, from the two groups, individuals who displayed similar pure-tone thresholds. Our experimental question, then, is this: *If an individual has a high-frequency hearing loss, is there any way to decide whether the loss was caused by steady noise or by gunfire?*

## SUBJECTS

*Gunfire (G).* The G group consisted of policemen, including several instructors at a police firing range. Most of these men had seen extensive action in the services, but few had ever worked in a noisy industry. Those who answered "yes" to the standard questionnaire item: "Have you ever

worked in a steady noise that was so loud that you had to shout in order to be heard?" were eliminated from further study (unless questioning showed that they were referring to the firing range itself).

*Noise (N).* The members of the N group were workers in an industry where the noise was particularly invariant. Ordinarily, it is difficult to specify the actual exposure of men to noise, since the level and spectrum may vary with specific location, and may also fluctuate in time. In this case, however, the entire working area was enveloped in a uniform noise of 104 db SPL overall (95 db SPL in the 600-1200- and 1200-2400-cps octave bands). After several years of work in this noise, all men show HLs of 30 db or higher in the 3-6 kc region (10).

In selecting men to be tested, we eliminated those who admitted more exposure to gunfire than that experienced in basic training in the services. Ideally, we would prefer to study only men who had not even had this basic training, but such a stringent criterion would have left us with only a handful of men. In addition, we excluded men who reported a particular incident involving gunfire that they felt might have affected their hearing. Exceptions to these exclusions were made for men whose pre-employment audiograms, made after the military service or particular incident, indicated normal hearing. That is, if the man began work with known normal hearing, all prior history was disregarded. (We had been testing men regularly in this plant for about 8 years.)

*Selection principles.* It may be true that gunfire may produce more conductive loss than steady noise--or vice versa. But since we were interested here only in high-frequency losses, it was required that all ears to be tested had a HL (American standard) of 10 db or lower at 1000 cps and 40 db or higher at 4000 cps. Although this criterion would not eliminate ears with conductive impairments amounting to less than 10 or 15 db, at least we were guaranteed an absence of advanced otosclerotics.

Similarly, we did not want to have to consider the possible confounding effects of presbycusis, so only men younger than 46 were included. Recent research has shown that presbycusis--the decrease in hearing sensitivity to air-conducted tones due to the aging process alone--is negligible until after age 50 (4). The research cited emphasizes that the gradual increase of HL with age in a random sample of the population of the United States--or in a not-so-random sample of fair-goers--that has in the past uncritically been termed "presbycusis", in reality represents both presbycusis and "sociocusis" (5). That is to say, in such surveys the effects of

aging are inextricably mingled with the cumulative effect of the auditory traumata of everyday living: blows on the head, disease, anoxia, firecrackers, etc.

A list of 25 men who met the stated criteria for the N group was sent to the plant personnel manager, who arranged to have the men come in for testing after three days of rest from the noise. This was possible because the men received one 4-day weekend off every month. In this way, the confounding effect of temporary threshold shift was minimized. Of the 25 men on this list, 3 had resigned during the interim between our survey of the hearing of the entire group and the initiation of the present program. One man of the remaining 22 refused to participate, and another was found at interview to have had considerably more exposure to gunfire than his questionnaire indicated. All men were paid liberally for their time, but as far as we know, no particular pressure was brought to bear by the management, so the 95% completion was very gratifying.

After testing of the N group had begun, the G group was recruited. Ten men previously testing at the firing range met the prescribed criteria; 8 of these came in for the extended testing. To augment this G group, a second survey was run at the firing range. In this case, we asked all the men who were there for their monthly "qualifying" shooting to come into our mobile laboratory for testing. Of the 67 men who did so, 27 were found to have the required hearing loss; 13 met the other criteria and were asked to come down for further testing, and 10 of these 13 finally appeared. (It must not be assumed, however, that 27 out of 67, or roughly 40%, of all policemen have HLs of 40 db or more at 4000 cps. It is very likely that men who had noticed hearing loss would be more willing to spend the time to find out how great the loss was, so that the percentage of high HLs measured here is higher than one would get in a random sample of all policemen.) In all, 18 policemen were finally tested.

The two groups were well matched in terms of age; the median age for both groups was 37 years. While no formal measure of socio-economic level was taken, it was felt that the groups were roughly equivalent in this regard; in contrast to most noisy factory positions, the jobs of our N group are high in prestige and pay, since a high degree of mechanical skill is involved.

## PROCEDURE

Figure 1 is a block diagram of the apparatus. Two oscillators were alternately fed to an electronic switch by means of one section of a rotating cam-and-microswitch assembly S2. Other sections of the assembly con-

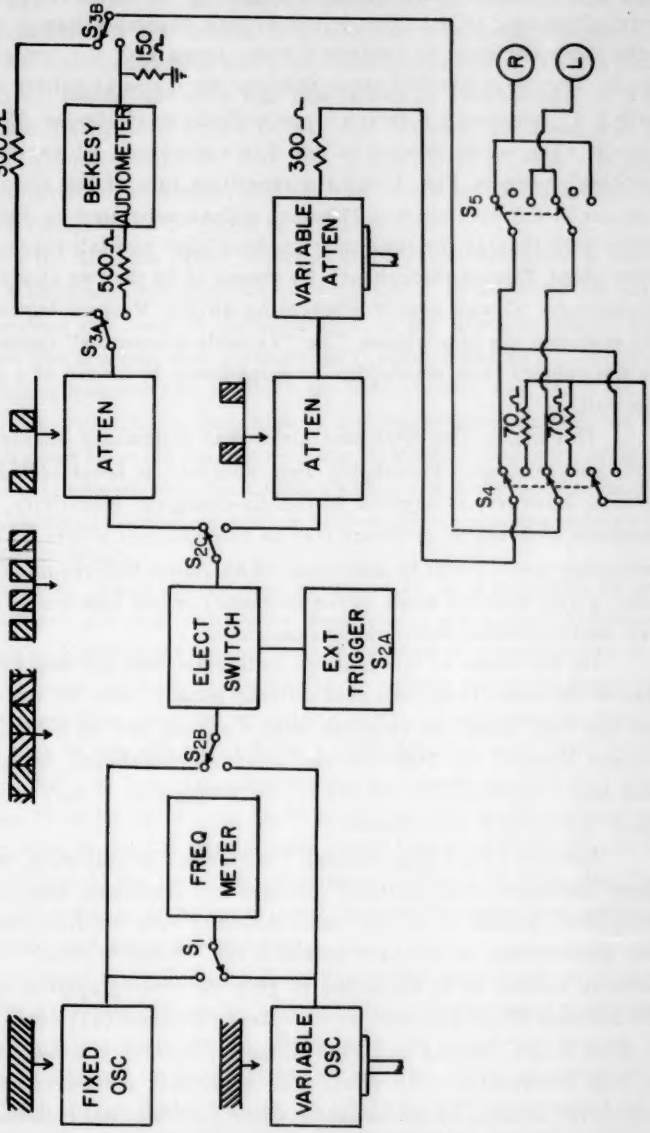


Fig. 1. Block diagram of apparatus.

nected the output of the electronic switch to two different 600-ohm attenuators (S2C) and provided external triggering so that switching transients were eliminated (S2A). The period of this assembly was 3 sec., and the cams were adjusted to produce 0.8-sec tones with 0.7 sec of silence between. The cross-hatched areas indicate the temporal pattern of the signal. Switch S3 introduced a Bekesy-type audiometer (Rudmose ARJ-3) into the circuit; when it was desired to use this audiometer, S2 was stopped at the position shown in Fig. 1 and the repetition rate of the electronic switch was set at 0.5 sec, so that 250-msec pulses separated by 250 msec of silence went through the top output channel (rise- and fall-times of the pulses were about 20 msec throughout). By means of S4 the two channels could be recombined; S5 was simply a reversing switch. Various impedance-matching resistors are also shown. The "variable attenuator" could be adjusted by the subject from inside the listening booth by means of a shaft through the wall.

*Threshold*. The first test given was a detailed audiogram on both right and left ears. Thresholds were obtained at least at half-octave intervals; however, in regions of rapidly-changing sensitivity, enough frequencies were tested to insure that no two adjacent points on the resultant audiogram would differ by more than 10 db. About halfway through the experiment, a very detailed study of the frequency region just below the tonal gap was added to these threshold measurements.

On the basis of the detailed audiogram, one ear was chosen for the rest of the tests. If the two ears differed greatly, then the ear selected was the one that fitted the criterion best--i.e., the one with the greatest difference between the 1000-cps and 4000-cps thresholds, or the one whose loss began earliest (i.e., at the lowest frequency). If they were nearly the same, the left ear was chosen.

*Albrecht effect (tone decay)*. Sometimes a steady tone, initially well above threshold, will gradually get less and less loud, until it disappears altogether. Kobrak et al (8) credit Albrecht with the first observation of this phenomenon, so we have termed it the "Albrecht effect" even though, because Kobrak et al neglected to give the bibliographical reference, we are not sure *which* Albrecht was involved. Schubert (11) studied the effect at great length, finding that even in normal observers it was often present at high frequencies. The effect was especially pronounced in ears with perceptive losses, so we thought it quite possible that if indeed there were morphological differences between noise- and gunfire-induced losses, there might also tend to be differences in severity of Albrecht effect.

The procedure employed here was that developed by the Northwestern group (1). An interrupted tone was presented to the ear of the listener, and he was asked to adjust the variable attenuator so that the tone was just audible. (Whenever the method of adjustment was used, the subject was instructed--and required--to use a bracketing procedure.) After a short (5-10 sec) silent period, the tone was now turned on continuously at 5 db SL. If the tone disappeared before 60 sec had elapsed, the level was increased 5 db (without turning the tone off). If this 10-db-SL tone also disappeared within the next minute, the SL was raised to 15 db, and so on, until the tone continued to be heard for a full minute.

Testing for Albrecht effect began at the highest frequency at which the subject's threshold was sensitive enough that a 10-db sensation level would not exceed the limit of the apparatus. If the Albrecht effect were present, then the process was repeated at a lower frequency, continuing until a frequency was reached at which the 5-db SL tone was heard for the required minute. Progressing from high to low frequencies, rather than the reverse, was done to avoid confounding the Albrecht effect with ordinary post-exposure temporary threshold shift (TTS), since the sound pressure levels of even 5-db-SL tones were often high enough to produce measurable TTS in normal listeners.

*Recruitment.* Since recruitment is known to be a correlate of end-organ impairment, the next tests were designed to reveal any differences that might exist between the groups in terms of rate or completeness of recruitment. In order to train the subjects in making equal-loudness judgments, they were first required to make a series of adjustments equating a 1000-cps tone in the left ear (LE) to a 1000-cps tone at a fixed level in the right ear (RE). At least two adjustments were made at each of 7 levels ranging from 25 to 85 db SPL in 10-db steps. In half of the training tests the variable tone in the LE was initially lower than that in the RE, and in half it was higher. If the two final adjustments differed by more than 5 db, additional adjustments were made until the experimenter was satisfied that the subject had become consistent.

After a short rest, equal-loudness judgments were made at loudness levels of 25, 45, 65 and 85 phons at 3 or 4 frequencies, using a monaural technique in order to minimize the effects of slight conductive losses. The signals were combined by means of switch S4 (Fig. 1) and presented to the test ear. The fixed oscillator was set at 1000 cps, and the intensity of this tone was set at say 25 db SPL. The subject adjusted the other tone, set

at a higher frequency, to produce equal loudness. The intensity of the 1000-cps tone was now changed to 45 db SPL and another adjustment made, and so on. Two series of determinations were made: one in which the four judgments at one frequency were completed before going to the next higher frequency (as just described), and one in which all the judgments at one loudness level were completed before changing to the next higher level. Again, additional adjustments were required if the two readings differed by 8 db or more.

The frequencies at which these recruitment measurements were made included one whose threshold was about 20 db HL, one at about 40 db HL, one near the peak loss, and, if the loss was a true tonal gap instead of simply a high-frequency cutoff, one in the region of normal sensitivity above the gap.

*Speech tests.* Finally, tests for perception of speech were given, using a Grason-Stadler Speech Audiometer Model 162. Spondee threshold for the test ear was determined, and then two PB lists were presented at a level 40 db higher. Finally, after a short break, a consonant-confusion test designed particularly for this study was presented. This test is described below.

Since all the ears concerned were normal at 1000 cps and below, and most were nearly normal at 2000 cps, it was clear that there would not be much impairment of speech comprehension as measured with the ordinary PB lists. Certainly errors in identification of vowels would seldom occur. What was needed, therefore, was a test that examined only confusion among consonants. The Rhyme Test developed by Fairbanks (3) was first considered. However, it appeared that a man's hearing would have to be poorer than was expected of the present subjects for him to hear "pot" as "not" or "hot", or to hear "way" or "bay" instead of "say".

The solution to the problem consisted of combining the form of the Rhyme Test with the data of Miller and Nicely (9). These authors used the vowel "ah" preceded by various consonants, and tabulated the frequency of occurrence of all responses when the speech was filtered or mixed with noise. The data indicated that certain consonants were more easily confused than others. In particular, the following groups of consonants displayed a high degree of intra-group confusion: (1) p, t, k; (2) f, θ, s, ʃ; (3) b, d, g; (4) v, ð, z, ʒ; and (5) m, n.

We could of course have proceeded to use the same method as Miller and Nicely, i.e., present a series of (mostly) nonsense words by using a single carrier vowel such as "ah" with various consonants. Several ob-

jections were immediately obvious, however. First, we would either have to teach the subjects phonetic spelling or have them repeat what they thought they heard. The former alternative seemed impractical, the second of course requires that the experimenter make no mistakes in recording the subject's responses (one of the chief drawbacks of PB-list testing). In addition, we were confident that the men would take much more seriously a test using real words than they would one with nonsense syllables. Finally, statistical treatment of the results would be easier (or at least somewhat clearer) if the number of possible responses were specified instead of being indefinite. That is, if the listener knew that the word was one of exactly N words, then one could correct the data for guessing, a correction that is hardly possible when the number of possible responses is indefinitely large or varies from word to word (as in the PB lists). Therefore, it was decided to try to set up a test in which the subject was required to choose between two real monosyllabic words differing only in having different easily-confused initial consonants.

Accordingly, an attempt was made to collect 10 real words that differed only in the initial consonant for each comparison. It would have been desirable to use 10 different vowels in these words, since the acoustic characteristics of the preceding consonant may change appreciably with a change in vowel. However, this was not always possible.

For certain confusion groups, 10 sets of words could be found that used each consonant in the group. In pairs involving p, k and t, for example, "pick" could be matched against both "tick" and "kick". Other words included tall, tart, tare, tan tone, tool, teal, try and tut, together with the corresponding words starting with p and k. Similarly, for comparing b, d and g, the words used were dear, dig, dote, dirt, die, door, doe, day, dun and debt, and their correlates using b and g.

Only two complete sets of common words could be found for the fθsʃ group -- "sin" and "sigh" and their rhymes. By using proper names and rare words, three more were added: sore, sill and sole. For the remainder of the pairs, the only criterion was that as many different vowels as possible be used.

The real trouble came with vðzʒ group. Since no words start with ʒ, this consonant was eliminated. In addition, there simply are not 10 words starting with ð that also start with either v or z. So in this case it was necessary to allow the key consonant to occur at the end of the monosyllable part of the time. (Perhaps it would have been better to allow nonsense syllables in this instance, but this is a matter for future research.)

Even then, rare words had to be used, such as rive, vair and lave, for example.

In addition to the comparisons suggested from the Miller and Nicely data, the following groups of phonemes were pitted against each other: *w-hw-h*, *b-v*, *tʃ-ʃ*, and *dʒ-tʃ*. The final test, then, included 220 pairs of words contrasting 22 different pairs of phonemes, broken down into 2 lists of 110 pairs each. The subject was given an answer sheet with the pairs of possible words printed in capital letters on them, and was asked to draw a line through the one heard. The word actually spoken was chosen by a random process, but with the constraint that of the 10 comparisons of any two sounds, 5 of each were to be correct. The spatial position of the correct item was also randomized. Each successive bank of 22 items included one comparison of each phoneme pair.

The words were spoken by the senior author (midwestern accent) and put on tape. Four different tests were prepared; however, two of these were just the opposite of the first two, so to avoid artifacts only the first two (i.e. 4 half-lists) were used in the present study. Words were presented at a rate of 24 per min, so a 110-item half-list required about 5 min.

A series of exploratory studies using normal subjects but simulating high-frequency losses by filtering the tape showed that with progressively lower cutoff frequencies, many of the choices became difficult to make. In certain cases, the "incorrect" word was chosen by all listeners. For instance, the word "sake" clearly changed to "fake" when a cutoff frequency of 2000 cps was used, and with 1700 cps cutoff, "gaze" changed to "gave" and "sole" changed to "thole".

In the present study, the subjects were given successive half-lists at progressively lower levels. The first list was presented 40 db above spondee threshold, the second at 30 db, the third at 20, and the fourth at 10 db.

The entire series of tests took about 4 hr. If anyone finished earlier, the remaining time was spent in gathering additional equal-loudness judgments.

## COMPARISON OF GROUPS: PURE TONE-MEASUREMENTS

Casual inspection of the detailed threshold data indicated that the average loss of the N group began at a slightly lower frequency than that of the G group. Therefore, the first step was to match as many ears from the two groups as possible in terms of this factor. A "cutoff" frequency was determined for each of the experimental ears. This was the numerical average of the frequency at which the HL became 30 db greater than at 1000

cps and that at which it became 40 db greater. It was possible to match 16 pairs of ears fairly well in cutoff frequency, so that only 2 ears from the G group (cut-off frequencies of 3.7 and 4.1 kc) and 4 from the N group (2.1, 2.2, 2.3 and 2.5 kc) had to be omitted from the comparisons that follow.

Figure 2 shows the detailed threshold sensitivity of all 32 ears, by

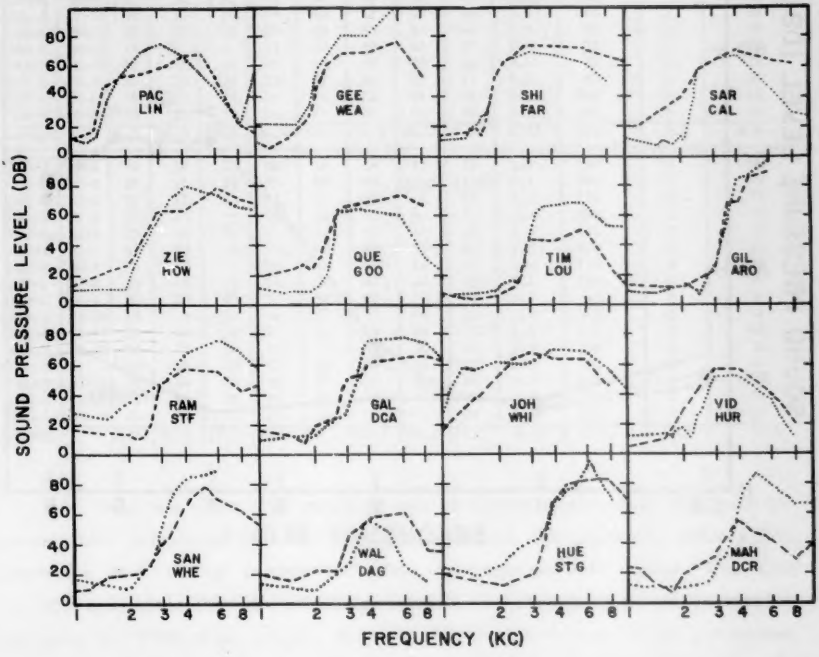


Fig. 2. Pairs of detailed audiograms matched in terms of "cutoff" frequency (see text). The dashed lines and the top subject identification code (e.g. PAC) denote members of the N group (hearing loss probably attributable to steady noise); the dotted lines and bottom identification code (e.g. LIN) indicate members of the G group (loss probably attributable to gunfire).

matched pairs. Although one cannot of course expect two audiograms matched at a single point to coincide at all frequencies, the differences are not unreasonable, and on the average the two groups are nearly indistinguishable. This is illustrated in Fig. 3, which shows the average thresh-

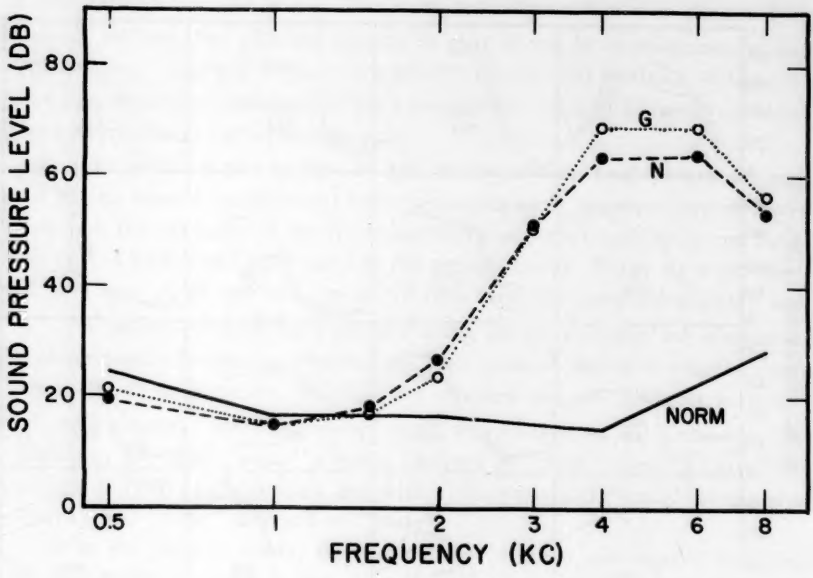


Fig. 3. Mean thresholds at standard audiometric frequencies for the two groups of subjects. The dashed line indicates the N group and the dotted line the G group. The present audiometric normal (for PDR-8 earphones in MX-41/AR cushions) is shown as a solid line.

olds at the frequencies tested on all ears for the two groups (the solid line represents the present American standard normal for PDR-8 earphones in MX-41/AR cushions). Individual and average thresholds and cutoff frequencies are given in Table 1. Also included in this table are the following measures:

TABLE 1

Pure Tone Data on Matched Subjects

| Name | No. | 500 | 1000 | 1500 | 2000 | 3000 | 4000 | 6000 | 8000 | Cutoff Freq. (kc) | Max Slope (db/oct) | Tone Decay Index | Recruitment Index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PAC-L | N-1 | 15 | 11 | 45 | 54 | 59 | 67 | 52 | 21 | 1.7 | 195 | 0 | 30 |
| GEE-L | N-2 | 15 | 9 | 11 | 27 | 67 | 70 | 73 | 52 | 2.1 | 340 | 2 | 26 |
| SHI-L | N-3 | 22 | 13 | 18 | 53 | 72 | 74 | 73 | 62 | 2.0 | 170 | 1 | 36 |
| SAR-L | N-4 | 31 | 20 | 31 | 40 | 66 | 72 | 66 | 64 | 2.4 | 90 | 0 | 34 |
| ZIE-L | N-5 | 11 | 13 | 21 | 26 | 63 | 63 | 79 | 72 | 2.5 | 95 | 2 | 32 |
| QUE-L | N-6 | 25 | 18 | 23 | 26 | 64 | 67 | 71 | 66 | 2.6 | 100 | 3 | 37 |
| TIM-L | N-7 | 18 | 8 | 4 | 6 | 44 | 48 | 50 | 25 | 3.1 | 205 | 2 | 39 |
| GIL-R | N-8 | 16 | 14 | 12 | 11 | 23 | 67 | 78 | (100) | 3.3 | 235 | 3 | 21 |
| RAM-L | N-9 | 20 | 18 | 15 | 15 | 50 | 58 | 56 | 44 | 3.5 | 305 | 0 | 37 |
| GAL-L | N-10 | 20 | 18 | 10 | 17 | 50 | 61 | 65 | 66 | 3.4 | 280 | 2 | 32 |
| JOH-L | N-11 | 22 | 16 | 35 | 50 | 68 | 63 | 63 | 46 | 2.5 | 40 | 1 | 34 |
| VID-L | N-12 | 15 | 5 | 8 | 29 | 57 | 55 | 41 | 23 | 214 | 65 | 2 | 30 |
| SAN-L | N-13 | 17 | 10 | 19 | 20 | 40 | 69 | 69 | 62 | 3.2 | 95 | 0 | 23 |
| WAL-L | N-14 | 25 | 20 | 16 | 23 | 47 | 58 | 62 | 37 | 3.7 | 90 | 0 | 29 |
| HVE-R | N-15 | 18 | 21 | 17 | 14 | 21 | 72 | 84 | 84 | 3.6 | 360 | 3 | 40 |
| MAH-R | N-16 | 28 | 25 | 10 | 19 | 31 | 55 | 42 | 30 | 3.6 | 130 | 0 | 39 |
| Average | | 19.9 | 14.9 | 18.4 | 26.8 | 51.4 | 63.6 | 64.0 | 53.4 | 2.85 | 175 | 1.3 | 32.4 |
| LIN-L | G-1 | 19 | 10 | 25 | 58 | 74 | 68 | 47 | 23 | 1.7 | 155 | 0 | 36 |
| WEA-L | G-2 | 26 | 21 | 21 | 35 | 80 | 80 | (100) | (100) | 2.1 | 280 | 3 | 40 |
| FAR-R | G-3 | 20 | 11 | 20 | 51 | 70 | 68 | 64 | 51 | 2.0 | 175 | 0 | 33 |
| CAL-L | G-4 | 20 | 15 | 9 | 14 | 65 | 68 | 46 | 30 | 2.4 | 245 | 1 | 26 |
| HOW-L | G-5 | 15 | 19 | 11 | 11 | 57 | 79 | 74 | 65 | 2.6 | 115 | 1 | 29 |
| GOO-R | G-6 | 19 | 10 | 8 | 8 | 61 | 61 | 59 | 31 | 2.7 | 215 | 1 | 34 |
| LOU-L | G-7 | 17 | 7 | 8 | 10 | 46 | 64 | 68 | 53 | 3.0 | 190 | 0 | 29 |
| ARO-L | G-8 | 23 | 9 | 8 | 11 | 27 | 83 | 97 | 93 | 3.4 | 560 | 1 | 37 |
| STF-L | G-9 | 24 | 25 | 25 | 36 | 48 | 69 | 77 | 60 | 3.7 | 45 | 1 | 33 |
| DCA-L | G-10 | 19 | 9 | 12 | 12 | 27 | 75 | 78 | 75 | 3.3 | 390 | 3 | 36 |
| WHI-R | G-11 | 24 | 26 | 56 | 61 | 61 | 69 | 68 | 57 | 2.8 | 130 | 0 | 40 |
| HUR-R | G-12 | 20 | 12 | 14 | 17 | 51 | 52 | 37 | 11 | 2.8 | 250 | 0 | 34 |
| WHE-R | G-13 | 19 | 16 | 13 | 11 | 55 | 79 | 88 | (100) | 2.9 | 130 | 2 | 41 |
| DAG-R | G-14 | 21 | 14 | 11 | 10 | 27 | 55 | 26 | 16 | 3.7 | 155 | 1 | 28 |
| STG-L | G-15 | 36 | 25 | 20 | 26 | 43 | 70 | 97 | 70 | 3.7 | 140 | 3 | 35 |
| DCR-L | G-16 | 24 | 15 | 12 | 10 | 20 | 60 | 78 | 66 | 3.9 | 180 | 2 | 40 |
| Average | | 21.6 | 14.6 | 17.1 | 23.8 | 50.7 | 68.7 | 69.1 | 56.3 | 2.92 | 210 | 1.2 | 34.4 |

(1) *Maximum slope.* The maximum rate of change of threshold SPL with frequency was calculated from the detailed audiogram. For instance, subject PAC showed a 10-db change in threshold when the frequency was changed from 1400 to 1450 cps; since this 50-cps change represents a change in frequency level of 61 cents (61/1200 of an octave), the rate of change here was 195 db per octave.

(2) *Severity of Albrecht effect.* It was difficult to satisfactorily reduce the tone decay data to a single interval-scale number. This difficulty arose from the fact that on different ears, different frequencies were tested for Albrecht effect. The best that could be done was to assign a category rank of 0, 1, 2, or 3 on the basis of the following criteria. If, at any frequency through 8 kc, the intensity had to be raised by 20 db or more above the starting level of 5 db SL in order to be heard for the required minute, the category assigned was "3". If the maximum effect were 15 db, the ear was designated "2"; similarly, a 10-db increase at 8 kc or below was a "1". If the ear either showed no Albrecht effect or only a single disappearance (i.e. only a 5-db increase was necessary) then the rating was "0".

(3) *Recruitment index.* Again, it was not possible to embrace all aspects of the equal-loudness judgments under a single index. However, one of the many possible indices is given in the table. This index is the difference in db between the 25- and 85-phon loudness levels at that frequency where threshold was 50 db SPL (35 db HL, approximately). The values were usually determined by interpolation. For example, subject LIN had a threshold SPL of 46 db at 1700 cps and 62 db at 2000 cps. At 1700 cps, a 40-db change of intensity was required to change the loudness level from 25 to 85 phons, while at 2000 cps only 25 db was needed. Therefore, the intensity change at that frequency whose threshold was 50 db SPL would be 40-15(4/16), or about 36 db. That this interpolation is justified will be clear later (Fig. 8).

It can be seen that there are no consistent differences between the matched pairs in terms of any of the indices. The only difference big enough to necessitate testing for statistical significance was maximum slope, and this difference was found not to be significant at even the 10% level of confidence.

Apparently, then, none of the pure-tone measurements made here will provide a very sound basis for deciding whether any particular high-frequency loss was produced by steady or by impulsive noise. It may be true that the "average" industrial steady noise (whatever that may be) tends to produce losses with a less precipitous slope than the average gunfire, simply because it produces more loss at lower frequencies, but it appears that a great number of authenticated cases of loss due to each would have to be gathered before even group differences would become significant. Recruitment seems to be a function of HL for all gaps, no matter how produced, and tone decay is sometimes present, sometimes absent, for nearly identical losses.

## COMPARISON OF GROUPS: SPEECH TESTS

However, consistent differences between the groups in speech discrimination scores were found. Table 2 shows the various measures for each ear (subject numbers are the same as in Table 1). Despite the fact that the average spondee thresholds were the same, the G group gave consistently fewer errors on the PB lists and the consonant-confusion tests at all levels. For all 5 of these indices the observed mean differences between the (correlated) scores were significant at the 0.1% level or beyond.

TABLE 2

Speech Test Results

| Subject Number | Spondee Threshold (db SPL) | Errors, PB Lists | Consonant-confusion Test 40 db SL | 30 db SL | 20 db SL | 10 db SL |
|---|---|---|---|---|---|---|
| N-1 | 10 | 16 | 10 | 17 | 22 | 23 |
| N-2 | 10 | 8 | 12 | 26 | 21 | 29 |
| N-3 | 8 | 9 | 17 | 17 | 22 | 30 |
| N-4 | 20 | 16 | 13 | 11 | 19 | 25 |
| N-5 | 8 | 5 | 13 | 21 | 25 | 30 |
| N-6 | 20 | 15 | 13 | 19 | 17 | 30 |
| N-7 | 4 | 2 | 9 | 15 | 22 | 20 |
| N-8 | 8 | 5 | 14 | 20 | 23 | 26 |
| N-9 | 10 | 7 | 8 | 14 | 20 | 22 |
| N-10 | 12 | 6 | 5 | 10 | 18 | 22 |
| N-11 | 12 | 9 | 11 | 20 | 18 | 23 |
| N-12 | 6 | 12 | 8 | 5 | 14 | 23 |
| N-13 | 10 | 4 | 10 | 10 | 10 | 21 |
| N-14 | 10 | 5 | 9 | 13 | 23 | 17 |
| N-15 | 18 | 6 | 8 | 8 | 8 | 8 |
| N-16 | 12 | 4 | 2 | 4 | 5 | 6 |
| Average | 11.1 | 8.1 | 10.1 | 14.2 | 17.8 | 22.2 |
| G-1 | 10 | 9 | 4 | 14 | 23 | 26 |
| G-2 | 12 | 8 | 15 | 12 | 25 | 17 |
| G-3 | 16 | 17 | 10 | 11 | 12 | 21 |
| G-4 | 6 | 10 | 7 | 11 | 17 | 29 |
| G-5 | 8 | 7 | 6 | 9 | 10 | 20 |
| G-6 | 16 | 3 | 3 | 3 | 3 | 10 |
| G-7 | 4 | 3 | 4 | 6 | 7 | 20 |
| G-8 | 6 | 1 | 9 | 10 | 10 | 14 |
| G-9 | 16 | 5 | 5 | 7 | 6 | 15 |
| G-10 | 8 | 4 | 4 | 11 | 15 | 32 |
| G-11 | 20 | 19 | 13 | 21 | 24 | 20 |
| G-12 | 6 | 6 | 4 | 9 | 9 | 23 |
| G-13 | 8 | 1 | 3 | 10 | 9 | 16 |
| G-14 | 6 | 0 | 4 | 7 | 8 | 16 |
| G-15 | 20 | 2 | 7 | 8 | 15 | 17 |
| G-16 | 8 | 3 | 3 | 4 | 2 | 12 |
| Average | 10.6 | 6.1 | 6.3 | 9.2 | 12.2 | 19.2 |

The next question one must ask is to what extent the differences in score are a result of differences of hearing rather than of other factors that are irrelevant in the present context, such as intelligence and education. An indication of the answer to this question can be obtained by analyzing the distribution of errors on each phoneme pair. If the differences are due to a central factor such as intelligence, then one might expect approximately the same ratio of errors between the N and G groups on each phoneme pair as on the test as a whole. If the differences reflect peripheral factors, however, then we might expect that certain phonemes should be confused more readily by the N group, and certain others should be confused more by the G group.

Accordingly, an analysis was made of the errors on each phoneme pair, combining data for all four levels. The total number of errors made by

the N group was 1034, by the G group 756. In other words, 57.8% of the errors were made by the N group, 42.2% by the G group. If the differences in performance were due to central factors, the errors on any phoneme pair should be distributed in the same proportion. For example, there were a total of 72 errors on words involving *m* and *n*. We would expect 57.8% of these errors (42) to occur in the N group, and 42.2% (30) to occur in the G group, if central factors are involved. The observed frequencies of 36 and 36 differ from the predicted values only at somewhere around the 15% level of confidence ($\chi^2$ with one degree of freedom). In this case, then, we cannot reject the hypothesis that the differences in group performance are due to central factors.

Of the 22 phoneme pairs, only 3 showed significant effects when tested in this way. On *s* vs. *θ*, for which 163 errors occurred, the N group made only 81 errors instead of 94, while the G group made 82 instead of 69. This is significant at about the .04 level; it can probably be dismissed as the one significant difference that one expects in 22 computations of $\chi^2$ even when the null hypothesis is true. The other two differences, though, cannot be explained away quite so easily. In the *ʃ*-*tʃ* comparisons, the observed frequencies of error were 71 and 28 instead of 57 and 42 ($p \sim .005$), and for *dʒ*-*tʃ*, 36 and 8 instead of 25.5 and 18.5 ($p \sim .002$). An even closer look at the data showed that the differences arose from three specific words: (1) in the N group 12 heard SHEAF as CHIEF, while only 2 of the G group made this error; (2) in the same test (i.e. at the same level) 10 of the N group heard CHEAP as SHEEP, as opposed to 2 of the G group; (3) the ratio of error in hearing CHET as JET was 10 (N) to 2 (G). Because the direction of the errors in the first two pairs is exactly opposite, the reason for the group differences--whatever it may be--is clearly not that the N group hears *ʃ* as *tʃ*, or vice versa. Possibly these differences represent a greater tendency on the part of the N group to choose the more familiar word when in doubt, although it is not clear why SHEEP should be more familiar to them than CHEAP.

These results indicate that the group differences in articulation scores are probably due to differences such as intelligence or education. The average number of years of schooling was 12.4 for the police, but only 9.8 for the industrial workers; whereas only 2 of the G group had not finished high school, only 2 of the N group had graduated. We do not think that motivational factors are involved; if anything, the N group appeared even more highly motivated than the G group. Apparently, though, this is not enough to overcome the educational disparity.

We therefore conclude that none of the measures used here will be of the slightest value in determining the probable cause of a given high-frequency hearing loss. Apparently a group of dead hair cells will always produce the same symptoms, regardless of the manner of their passing.

## CHARACTERISTICS OF LOSSES

Since, then, there are no consistent differences between noise-induced and gunfire-induced losses, the following sections will simply describe the characteristics of these tonal gaps and abrupt high-frequency losses, lumping both groups together and including the men who were not used in the matched comparisons.

*Pure-tone thresholds*. Several aspects of the threshold data deserve consideration. First of all, it is a common clinical impression that the higher the cutoff frequency of the loss, the steeper will be its sides. However, Fig. 4 indicates that this is not so, at least for the losses concerned here. This figure is a scattergram showing the relation between cutoff fre-

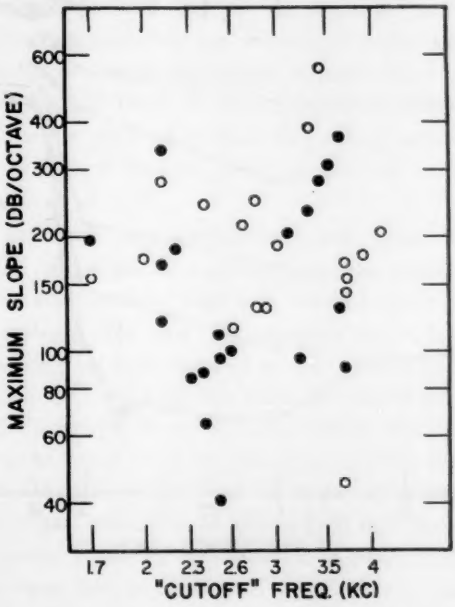


Fig. 4. Scattergram showing relation between cutoff frequency and maximum slope of audiogram (see text). Closed circles are for subjects of the N group, open circles indicate members of the G group.

quency and maximum slope (the latter plotted logarithmically) as defined earlier. It is clear that the correlation is not significantly different from zero. A little reflection suggests a reason for the erroneous impression that the steeper slopes are found for high frequencies. In ordinary clinical audiometry, the only frequencies commonly tested in addition to the octaves of 250 cps are 3000 and 6000. Therefore ears with notches centered at 3000 to 6000 cps will apparently show steeper sides than one centered at 2000 cps, but only because 1500 cps is not tested. For example, let us suppose that the threshold of a particular ear is actually 0 db HL at 1000 and 1500 cps, and 40 db HL at 2000 cps. If 1500 cps is not tested, the slope will appear to be 40 db per octave, whereas in reality it is at least 80 db per octave. (It can be seen that even with half-octave audiometry, the steepest apparent slope obtainable would be less than 200 db per octave;

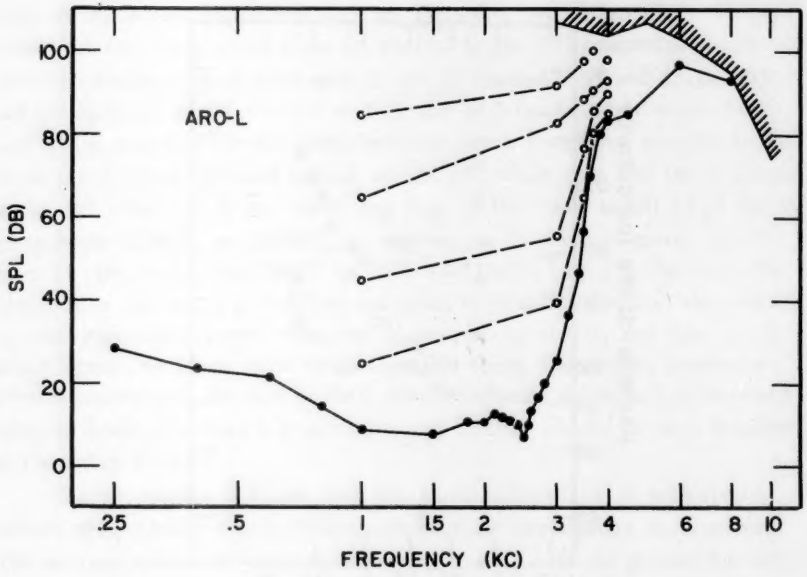


Fig. 5. Audiogram illustrating in detail the region of increased sensitivity often found just below a high-frequency abrupt loss or tonal gap. Dashed lines connect points of equal loudness .

if one wants to determine maximum slope, closely-spaced readings must be taken.)

A second comment concerns the nature of the threshold at frequencies just below the damaged region. In many cases, a region of apparently increased sensitivity can be found in this area. In Fig. 1, this phenomenon appears more in the G curves (dotted) than the N (dashed); however, this comes from the fact that a detailed search in this region was made in only the last half of the experiment, which included more G than N men. Figure 5 shows this phenomenon for ARO-L, who happens also to be the man with the sleepest slope (560 db/octave); in his case the "facilitation" appears at 2500 cps.

Now the region of increased sensitivity is not universally present; in about a third of the cases, the detailed search gave only a level curve. It might therefore be argued that the facilitation is artifactual--that if one looks closely enough at threshold in the frequency region 1-3 kc, one can usually find one or two of these "resonances", so that those observed need not have any connection with the tonal gap *per se*. However, we find that when they do appear, they are found *just* below the notch, and this argues against this otherwise reasonable hypothesis.

The physiological basis of this phenomenon is not clear; however, it may result from the absence of inhibitory firing normally contributed by the fibers just basalward from the area concerned--i.e., the fibers that are in this case inoperative.

Finally, the reader may already have been struck by the fact that in terms of peak HL (magnitude of maximum loss) the entire set of data (Fig. 1) are much more homogeneous than they would have to be on the basis of the selection criteria. The only requirements for inclusion in the study were normal hearing at 1000 cps and at least 40 db of loss at 4000 cps. Nevertheless, except for a very few ears, the maximum loss seems to be about 50 to 60 db HL (65 to 75 db SPL in Fig. 1). It is as though once this level is reached at a particular frequency, further loss at this frequency is slower to occur. In the case of the N group, this is perhaps not surprising, since it has already been shown (10) that the terminal HL after many years in noise (ignoring presbycusis) is proportional to the SPL of the noise, and these men, of course, all worked in the same level. However, the fact that it is also true for the G group, whose exposures were quite varied, suggests that a more basic principle is involved. One guess is that this "boundary" HL represents complete loss of the outer hair cells, but that the inner hair cells are still operative; this theory (2) requires the inner hair cells to have a 50- to 60-db higher threshold than the outer hair

cells. Another hypothesis is that by the time one reaches levels of this magnitude, the pattern of excitation on the basilar membrane is so broad that, even though both inner and outer hair cells in a particular area are completely unresponsive, there is enough excitation of normal areas (either basalward or toward the apex) to produce a neural discharge of nearly normal magnitude. Further research is indicated.

*Albrecht effect.* Abnormal tone decay appears almost capriciously in the data. Its severity does not appear to be related to any of the other measurements made (HL, slope, etc.) Given two ears nearly identical in threshold, one ear may show a large Albrecht effect while the other shows none. For example, subject SHI (Fig. 1) required a 15-db SL tone at 8, 6, 4, and 3 kc in order to meet the criterion of hearing for a full minute, while FAR, whose audiogram is nearly identical, heard a 5-db SL tone for the entire minute at these same frequencies. We cannot, therefore, predict with any certainty when the Albrecht effect will appear. However, we can say something about when it will not. In these ears, the tone-decay effect was always negligible at frequencies below the cutoff frequency (i.e., at frequencies below the gap having normal sensitivity). Also, in many cases the decay was zero at frequencies above the gap: PAC, for example, showed as much tone decay at 8 and 10 kc as he did at 3 and 4 kc. On the whole, these results confirm those of Schubert (11), who found large values of tone decay at moderate frequencies in persons with end-organ losses, and moderate values of tone decay at high frequencies even in normal listeners.

An unusual case of "accelerated" tone decay in one of the listeners is shown in Fig. 6. The threshold curve is itself unusual, in that despite a return to normal sensitivity at 8 kc, the threshold at 10 kc was not measurable with our apparatus, which means that it was somewhere about 75 db SPL. The numbers just below the threshold curve indicate the number of 5-db steps that the tone had to be increased above the initial 5-db sensation level. The values through 6 kc are quite typical, but at 8 kc the behavior was completely anomalous. Ordinarily, the higher the level, the longer the tone is heard. At 3 kc, for instance, this listener heard 5 db SL for 15 sec, 10 db for 20 sec, 15 db for 35 sec, and 20 db for a minute. However, at 8 kc the higher the intensity was raised, the more quickly the tone disappeared. At 5 db SL the tone lasted 25 sec, at 10 db 25 sec, at 15 db 30 sec, but at 20 db SL it disappeared in 15 sec. Further increases in level shortened the time even more, so that by the time the SPL reached 75 db (45 db SL) the tone was heard only 2 sec (these times are shown at the right in Fig. 6). At this point the test was terminated, in order not to produce any persistent effects that might affect subsequent tests.

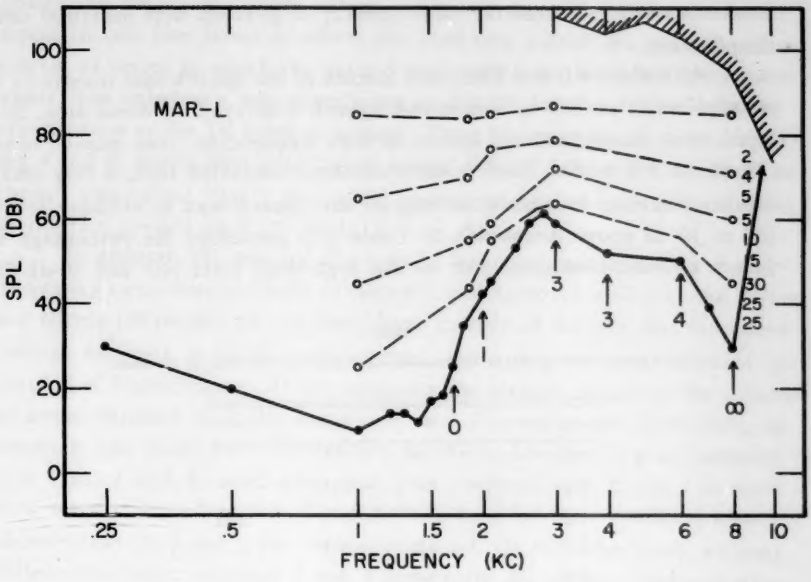


Fig. 6. Pure-tone data for a subject with accelerated Albrecht effect (see text). The numbers beneath the threshold curve (solid line) indicate the number of 5-db steps it was necessary to increase the intensity of a continuous tone at the indicated frequency (starting at 5 db SL) in order that the tone be heard for a full minute. The numbers at the extreme right show the number of seconds elapsing before an 8000-cps tone at the indicated level ceased to be heard.

These bizarre results appear to be related to those observed by Jerger (7) in 6 out of 10 cases of known acoustic neurinoma. When these subjects tried to track a continuous tone with a Bekesy audiometer, it was found that the intensity was allowed to reach the maximum obtainable with the apparatus with rather dramatic suddenness, a result that implies the same abnormal adaptation found here. Perhaps our listener also has an acoustic neurinoma; however, it is also possible that this represents merely a nar-

row "tonal island" (a small group of normal hair cells at 8000 cps surrounded on both sides by inoperative cells) that is unusually susceptible to threshold shift. Rapid disappearance of supra-threshold tones has also been observed (15) near the idiofrequency of persons with monaural tonal displacusis.

*Articulation tests.* The chief feature of the speech test results is the small loss of ability to understand speech displayed by these men. Despite their rather profound losses at high frequencies, they missed only 7% of the PB words. Even in the consonant-confusion test, a very small number of errors was made as long as the speech was at ordinary levels (40 or 30 db above threshold). In Table 3 is presented the percentage of errors on each consonant pair for the high-level lists (40- and 30-db SLs

TABLE 3

Breakdown of errors on Consonant-confusion test in terms of phonemes.

| Phoneme pair | H* | L** | S*** |
|---|---|---|---|
| s-ʃ | 5.9 | 9.7 | |
| s-f | 8.4 | 17.5 | |
| s-θ | 14.1 | 36.9 | 2.20 |
| ʃ-f | 1.9 | 4.4 | |
| ʃ-θ | 3.7 | 8.1 | |
| f-θ | 11.9 | 14.1 | 1.77 |
| v-ð | 30.3 | 34.5 | 1.54 |
| z-v | 14.1 | 27.5 | |
| z-ð | 16.9 | 26.6 | 1.67 |
| b-v | 13.1 | 17.5 | 4.15 |
| b-g | 0.3 | 2.8 | |
| b-d | 8.1 | 14.4 | 3.50 |
| d-g | 4.7 | 16.2 | 2.94 |
| p-k | 4.4 | 9.7 | 1.81 |
| p-t | 5.0 | 12.2 | |
| t-k | 6.9 | 17.2 | 1.96 |
| m-n | 9.4 | 13.1 | 2.79 |
| ʃ-tʃ | 4.4 | 26.6 | |
| tʃ-dʒ | 4.4 | 9.4 | 1.93 |
| w-hw | 31.0 | 35.0 | 3.49 |
| h-w | 0.9 | 0.3 | |
| h-hw | 1.9 | 3.8 | |

combined) and the lower-level lists (20- and 10-db SLs). The first phoneme of each pair listed (first column) is the one that was most often missed (called the other); the fourth column indicates the ratio of the number of errors (in all four lists) in which the first was called the second to the number of errors in which the second was called the first, for those pairs where this imbalance was significant at the 5% level. Italics indicate significance at the 1% level or beyond. Thus, for example, in pairs involving *s* and *θ*, words like "sin" were called "thin" 2.20 times as often as "thin" was called "sin"; the actual numerical ratio of 112 errors to 51 is significant beyond the 0.1% level.

In general, the pattern of errors is what one would expect if high-frequency cues were partially eliminated, and agree as well with the Miller and Nicely (9) results as one could hope in view of the fact that they used college students, a single carrier vowel, and a response population of 16 instead of 2 alternatives. If one compares the present results to the pattern of errors obtained by Miller and Nicely with filtered speech (200-2500), for example, one finds such similarities as the following: (1) *p* is confused with *t* and *t* with *k*, more often than p is confused with *k*; (2) *ʃ* is much less often confused with *s*, *f* and *θ* than the others are confused among themselves; (3) *b* and *g* are seldom confused. On the other hand, striking differences exist; although *b* and *d* apparently are seldom confused when linked to "ah" (Miller and Nicely), they are often missed when tied to other vowels (the same is true of *m* and *n*, it appears).

It was probably an error in judgment to use the group of phonemes *w-hw-h*, but these comparisons, it turns out, serve as a control indicator of sorts. The fact that only one error was made in discriminating *h* and *w* even at the lowest levels indicates that the subjects were not ever throwing in the towel at these low levels and simply marking at random. The inability to distinguish *w* and *hw*--e.g. WAIL and WHALE--depends both on auditory and cultural factors. Not only is the difference hard to detect, but some listeners (former New Yorkers, for instance) insist that they should be pronounced the same! It is probably not too surprising, then, that over 30% error was made even at the high levels.

Figure 7 shows the relation between the total percent error on the three highest level tests (40, 30 and 20 db SL) and cutoff frequency for the N (closed circle) and G (open) subjects. Although there is much variability, a gross relation can be discerned. We suspect that the lowest open point, (at 2.7 cutoff) represents an error in determining or recording subject GOO's spondee threshold (notice the discrepancy between his spondee threshold

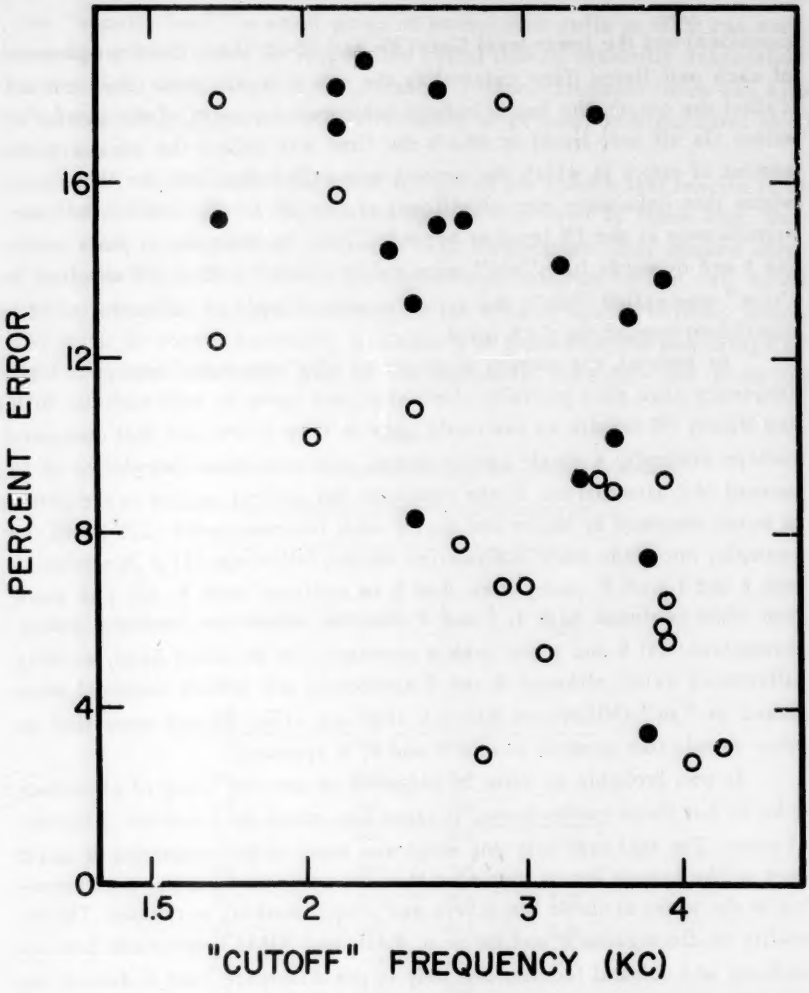


Fig. 7. Scattergram showing the relation between cutoff frequency and percent error on the consonant-confusion test, for both N (closed circles) and G (open) subjects.

[Table 2] and his absolute threshold from 1000 to 2000 cps [Table 1]), so that the speech tests were given to this subject 10 db higher than they should have been. Ignoring this point, the trend of the best performances suggests that an error-free result would be found if the cutoff frequency were 5 kc or higher.

These results constitute additional justification for the practice of considering hearing losses only at 2000 cps and below in estimating "handicap" in everyday speech perception (14). Little information is lost with loss of higher frequencies, and even this will generally be restored by context. After all, it is only rarely that one needs to distinguish the single word "pick" from "tick"; more usually it will appear in a sentence like "Pick out the one you want" or "Can you hear the watch tick?" Now it is true that some of the present listeners, especially in the N group, reported that their wives complained that they (the men) played the radio too loud, and that they could not hear them (the wives). However, much of this difficulty can doubtless be attributed to the nearly-chronic temporary threshold shift that these workers possess in the evening immediately after work. Besides, this type of complaint arises more than just occasionally even when the husband has completely normal hearing.

*Recruitment.* In order to derive a set of average recruitment curves, the combined data on equal-loudness judgments were divided into 6 different groups on the basis of the mean adjustment at the 25-phon level. That is data for all frequencies at which the average match to the 1000-cps tone at 25 db SPL was a tone of 30 to 39 db SPL comprised one subset; the next group contained data in which the average match was to a tone of 40 to 49 db SPL, etc. The number of recruitment functions in each subset of course varied, since each subject produced only 3 or 4 usable functions at best, and the results of half a dozen of the listeners were so variable that they were excluded from the analysis.

Table 4 presents the average results for these 6 groups, together

TABLE 4

Average SPL of Variable Tone Judged Equal in Loudness to a 1000-cps Standard Tone.

| | SPL of 1000-cps Standard Tone | | | |
|---|---|---|---|---|
| Group | 25 | 45 | 65 | 85 |
| 30-39 | 35.3 | 50.6 | 69.3 | 86.6 |
| 40-49 | 43.2 | 59.2 | 75.2 | 89.2 |
| 50-59 | 54.4 | 65.7 | 78.5 | 90.5 |
| 60-69 | 64.0 | 72.6 | 83.2 | 93.1 |
| 70-79 | 73.9 | 80.0 | 86.9 | 95.4 |
| 80-89 | 82.9 | 87.7 | 92.9 | 100.5 |

with the number of individual curves in each group. The consistency of the data appear more strikingly in Fig. 8. Quite clearly, the implications of these data is that recruitment is a linear process, and that it is complete at 100 db SPL, but not until 100 db SPL.

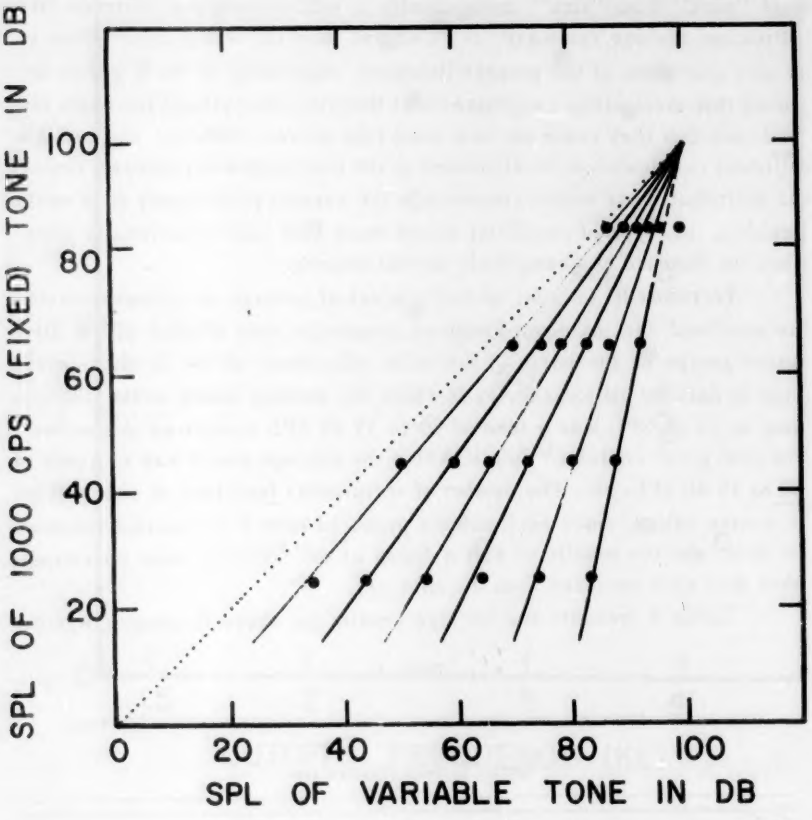


Fig. 8. Average recruitment functions for all subjects in the present study.

Of course, if one looks at individual data, one can find examples of all the myriad "types" of recruitment (S-shaped, asymptotic, over-recruiting, etc.). However, since we are not sure to what extent such departures from linearity are a result of slight departures from "normality" of the loudness function at 1000 cps in the ear concerned, or from random variability of judgments, we prefer to stress the lawfulness of the average results.

It may be wondered why we did not use threshold SPL instead of the match to 1000 cps at 25 phons as our basis of categorization. There were two reasons. First, only about halfway through the experiment did we begin determining threshold at the same time that the loudness judgments were made. Since it is known that the threshold determined by one technique may differ markedly from that indicated by another (in this case, Bekesy technique *vs.* adjustment), there was some doubt as to the propriety of mixing the two. Second, we wished to avoid having to assume *a priori* that two tones at threshold have the same loudness, an assumption one makes (usually tacitly) when threshold points are plotted on the recruitment functions. However, as it turned out, the analysis could indeed have been done equally well using threshold SPL as the categorizing factor. This is shown by the crosses in Fig. 8. The abscissa, for these points, is the threshold SPL for each subgroup averaged over the subjects whose threshold had been determined by the method of adjustment. All points lie on the 14-db line of the ordinate, because the mean threshold at 1000 cps with this method was 14 db SPL. Clearly, the threshold points fit the rest of the data well. We can, therefore, conclude with some confidence that two tones at threshold sound equally loud; in the present case, since the average threshold was 14 db SPL at 1000 cps, the loudness of the threshold tones was about 165 millisones. This figure follows from the fact that 1 sone is defined as the loudness aroused by a 1000-cps tone at 40 db SPL, and that loudness changes by a factor of 2 for each 10-db change in level (13).

The present data are indistinguishable from the average recruitment functions of 200 unilateral Meniere patients, recently reported by Hallpike and Hood (6). There are three points of similarity. (1) In most instances the *individual curves took the form of straight lines*, although there tended to be more over- and under-recruitment manifested than in the present results, because they could use a binaural technique (same frequency in both ears). (2) *The average curves are independent of frequency*. Hallpike and Hood show averages for 4 different frequencies: 500, 1000, 2000 and 4000 cps; although they maintain that the four sets of curves differ, it is

clear upon examination of their actual data and averages (6, p. 477) that the differences could not possibly be anywhere near statistical significance. (3) *The curves all tend to intersect at 85 db HL.* In the present set of data, SPL was used instead of HL. However, most of the curves are for frequencies from 1000 to 4000 cps, and through this range audiometric zero is nearly constant at about 15 db SPL, so that the point of intersection in Fig. 8, 100 db SPL, corresponds to about 85 db HL. This value appears to be quite close to what one would find for the Hallpike and Hood data if one treated it in the same way that we did ours. In their scattergrams, Hallpike and Hood plotted "recruitment angle" of the individual functions against HL and fitted a straight line to these points. Consequently their average results differ slightly from ours, since the implication of their treatment is that the recruitment angle in degrees increases linearly with HL, as contrasted with the present implication that normal loudness is attained at 85 db HL for any threshold sensitivity. However, the two formulations differ so slightly that additional research must be conducted to decide between them, although we feel ours is intuitively more appealing, as well as simpler. At any rate, they found the angle to increase with HL at about 0.5 degree per db. Therefore, since the angle will of course be 45 degrees at 0 db HL, it should become 90 degrees at 90 db HL, which is close to the 85-db-HL value of Fig. 8.

We conclude that measurements of recruitment will not aid in discriminating between high-frequency losses caused by acoustic trauma and those associated with Meniere's disease. This is not really a new finding: it has long been recognized that recruitment is found when end-organ pathology is involved, whereas it is absent when the trouble lies in the eighth nerve fibers. However, in hearing loss due to noise definite boundaries of damage to hair cells are usually found, while in Meniere's disease a rather diffuse deneration is observed over large areas of the organ of Corti. So when testing tones at the edge of a high-frequency loss, say where the HL was about 20 db, we had rather expected that the course of recruitment would be different from what would be observed in a case of Meniere's disease where the threshold change had reached 20 db over a large frequency range. In the case of Meniere's disease, raising the intensity would bring into play units on both sides of the area stimulated at low intensities, while in the case of a high-frequency loss contributions would come only from units on one side. Apparently in Meniere's disease the hypothesized contribution by elements on both sides is just balanced by the fact that on

both sides there are some inoperative elements, so that the net effect is the same as in the case of the high-frequency loss, where the fibers just apicalward are completely normal, although those just basalward are inoperative.

## SUMMARY

This study was conducted to test the hypothesis that the high-frequency losses produced by chronic exposure to steady noise differ in some distinct fashion from those caused by impulsive noise (specifically, gunfire). Two groups of men were tested; the N group had been exposed to a minimum of gunfire but had worked for several years in a high-intensity noise, while the G group had done much shooting but had never been employed in a noisy industry. The basis of inclusion in either group was the presence of a high-frequency hearing loss.

Sixteen members of each group were matched in terms of the frequency at which the HL became about 35 db greater than its value at 1000 cps. Comparison of these paired subjects revealed no average difference between G and N groups in (1) maximum slope of the audiogram, (2) incidence of abnormally rapid tone decay, or (3) slope of recruitment functions. Although there were consistent differences between the two groups in speech perception tests, analysis of the errors indicated that the difference can probably be attributed to the fact that the G group was better educated, hence presumably more intelligent. It is concluded that there is no way to determine whether a given loss was caused by steady noise or by gunfire.

The combined data for all ears was next inspected in a search for generalizations about the characteristics of high-frequency abrupt losses and tonal gaps in general. There was no correlation between the cutoff frequency of the loss and the maximum rate of change of HL, indicating that the higher-frequency notches are no "sharper" than the lower-frequency gaps. A region of increased sensitivity just below the tonal gap was often observed, an effect that is attributed to absence of inhibitory firing normally observed, an effect that is attributed to absence of inhibitory firing normally contributed by the fibers in the now dead or unresponsive area of the basilar membrane. Abnormally rapid tone decay was uncorrelated with any other measurable aspects of the hearing, being sometimes present, sometimes absent in ears with very similar audiograms. An unusual case of accelerated tone decay is described (Fig. 6); here progressively higher levels of tone at a "tonal island" disappeared more and more rapidly.

The errors made by the listeners in the speech tests were analyzed in terms of consonant pairs. The patterns of errors were similar to those observed in normal ears presented with speech sent through low-pass filters. The fact that even easily-confused consonants were usually discriminated correctly by these men with severe losses at 3000 and above supports the use of only 500, 1000 and 2000 cps in the determination of handicap due to hearing loss.

The average recruitment functions (Fig. 8) were very similar to those observed in Meniere's disease. Three main characteristics are emphasized: (1) the recruitment curve is a straight line, (2) recruitment is complete at 100 db SPL and not until 100 db SPL, for HLs from 0 to 70 db, and (3) the rate of recruitment is in no way dependent on frequency.

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# THE RELATION BETWEEN SPEECH INTELLIGIBILITY AND THE ELECTRO-ACOUSTIC CHARACTERISTICS OF LOW FIDELITY CIRCUITRY *

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## INTRODUCTION

Considered as a class of low fidelity communications systems, hearing aids represent a large number of compromises imposed upon ideal circuitry by considerations of size, weight, and cost. These compromises are reached by management from among the usually conflicting recommendations of the sales and engineering staffs. One can but admire the rate of growth of the industry, which serves such a vital need in our socioeconomic community, and the multiplicity of models, many of which quickly become obsolete by reason of truly new and valid developments in battery drain, transducer design, microminiaturization, etc.

One notes that these problems are not those alone of hearing aids but of the communications industry in general. Portable radios, small phonographs, intercoms, etc., all have the same compromises to make, and these must be made in the absence of fundamental data. Analyses by each manufacturer of consumer acceptability and preferences hardly qualify as basic information.

If in fact one closely examines the optimum electroacoustic characteristics of such circuitry for use under everyday speech conditions, it is found that very little pertinent data exist. We do not know, for example, what is the narrowest acceptable frequency bandwidth; in the case of music, listeners have even stated that they preferred a limited rather than an extended bandwidth. We do not know whether the frequency response should be flat or should exhibit a rising slope. We do not know the percentage of harmonic distortion at which speech intelligibility begins to be affected. We do not even have an idea as to which of many possible measures of intermodulation distortion should be looked into; as for transient distortion, no commercial loudspeaker is adequate even to begin the study of that probably crucial variable.

There are two deeply-rooted difficulties in attacking this field. First is the interrelations among electroacoustic indexes. For example, the frequency response characteristic may sharply influence the harmonic distor-

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tion at certain frequencies. This is a purely physical phenomenon. It is difficult, often impossible to vary a single characteristic while leaving all others without change, and complicated statistical procedures must be used to tease out the relative contribution of a particular electroacoustic index.

A second difficulty is that when two or more types of distortion, or noise in the broadest sense, in the circuit are added, the resultant loss in intelligibility is often much greater than a simple addition would predict. For example, two types of noise, either of which would by itself reduce intelligibility by only 5%, may when added reduce intelligibility to 50% or less. This is partly physical and partly it is a function of how the hearing mechanism codes and decodes speech. Thus the relative importance of a particular type of noise can be truly assessed only by looking at its interactions as well as its effect in isolation.

The purpose of the present series of experiments was to explore the dependence of intelligibility on some of the simpler electroacoustic characteristics of low fidelity circuitry; and if possible, in addition, to attempt a weighting or at least a ranking, of the electroacoustic characteristics in order of importance.[1-6] The purpose has been incompletely served, in that better instrumentation especially for transient distortion will shortly take such research another order of magnitude beyond the present state. Nevertheless, it is thought wise to spread our results before the reader at this time in order to serve in some part as a guide to later, more definitive work.

## EXPERIMENT 1: PROCEDURE

### 1: *SPEECH MATERIAL*.

It was first of all necessary to decide the type of speech material, the types of speech distortions to be used to degrade intelligibility, and the number of voices to be used.

*a. Type of speech.* Although single-word lists are very efficient in many respects, they obviously cannot well be used if one wishes to process speech with such types of distortion as reverberation, speed alteration, double-delay, and others in mind for this project. Colloquial sentences were decided upon. Of the many available, the best suited seemed to be the ten lists of ten sentences each, kindly loaned to us by Silverman and Hirsh composed according to rules laid down by a Working Group of the National Research Council–Armed Forces Committee on Hearing and Bioacoustics, Grant Fairbanks, Chairman. These lists are of homogeneous difficulty, in colloquial use, and the 50 key words in each list form a good sample of the phoneme content of English.

However, since these sentences are of extremely unequal length, the original 100 sentences were slightly rewritten so that each contained 6 – 9 words, while still retaining the 50 key words per list.

Because of the very marked retention once a subject has heard a particular sentence, it is possible to give any particular subject a particular list on only one occasion. Since 100 sentences per speech condition were needed, it was necessary to compose additional sets of 100 sentences each to be used under every other speech condition. Using the original 500 key words, the third-named author composed two more sets of 100 sentences each, again 6–9 words per sentence.

*b. Type of distortion.* The 1945 NDRC Aural Rehabilitation Project used three different types of distortion or noise in an attempt to degrade speech so that perfect or near-perfect scores would not be obtained, namely, white noise, peak-clipping, and bandpass frequency filtering. But we do not know whether these distortions, which are seldom met with in real life, can serve as a real sample of all the types of speech distortion encountered in everyday situations.

In the present work, 23 10-sentence lists were tape recorded using natural speech, denasal speech, speeded speech, speech while eating, reverberated, filtered, and interrupted speech, and combinations of these, with a total of 10 talkers. These lists were then presented a few at a time to groups of listeners, and a selection of Pearson product-moment correlations computed of talkers vs talkers and condition vs condition. List-to-list reliabilities ranged from .75 to .88 computed for each of four talkers. Intercorrelations from .1 to .46 (median $r = .25$) between 30 pairs of conditions led to the conclusion that three well-selected conditions yielding poor, average, and fair scores would suffice to sample condition variance.

The conditions chosen were: (1) natural speech, selected to yield intelligibility scores of about 75% through the average aids; (2) denasal-speeded speech, to yield scores of about 50% (talkers wore a swimmers' noseclamp and talked more rapidly than usual); and (3) interrupted speech (natural speech stored on tape and rerecorded through a Grason-Stadler switch and timer set at 5 msec rise-fall time, 8 interruptions per sec at 50% duty cycle) designed to yield scores of about 25%. This last is a somewhat artificial type of distortion, but interrupted speech is often encountered in the presence of intermittent noise.

*c. Voices.* Intercorrelations from 0 to .43 between certain of the 10 original talkers led to the conclusion that at least three and preferably five voices would be needed to sample talker variance. Five voices were finally selected: Lisa, age 8, intelligible child; Margie, age 35, medium pitched voice; Bernice, age 68, unusually intelligible slow speech; Bob, age 30, clear clipped voice; and Bill, age 35, low pitched relatively fast speech somewhat blurred by overbite. Thanks are due to these talkers for their willing cooperation.

*d. Final recorded sentences.* Each of the five talkers read the original 100 sentences in a natural voice into a W. E. 640 AA microphone, VU meter, and Ampex 300 tape recorder. Next, in a fairly extensive editing job, List A (first 10 sentences) was constructed by splicing together sentences 1–2 from Talker A, sentences 3–4 from Talker B...9–10 from Talker E; likewise for Lists B...J.

From the 100 sentences thus prepared, a latin square was arranged, such that with any group of 10 listeners the effects of fatigue, motivation, intersubject and interlist effects, etc., were counterbalanced. An average performance score for any aid, then, finally arose from exactly the same sentences, talkers, and listeners as every other aid for any condition.

This whole procedure was of course repeated with the second and third set of sentences, Lists $A_2$–$J_2$, $A_3$– $J_3$ under the denasal-speeded, and the interrupted conditions.

Once the 300 sentences were thus prepared, and the 10 aid/conditions had been selected as explained below, the 300 sentences were fed from a Fairchild Model 126 studio tape recorder to a Jensen 15-inch loudspeaker in an anechoic chamber, picked up at the desired SPL by each aid/condition in turn, the output of the aid fed to an ASA 2cc coupler fitted with a W. E. 640 AA microphone, and stored again in an Ampex 300 tape recorder.

*2: ANALYSIS OF HEARING AIDS.*

A dozen hearing aids were given the following tests:

(a) Frequency response curve of SPL output from 200 – 5000 c/s, full-on gain, minimum SPL input for maximum output

(b) Frequency response curves of SPL at 50, 60, 70, and 80 db input; gain 40 db at 1 kc with 60 db input

(c) Frequency response curve of SPL, 62½ SPL input; gain set for maximum of 10% harmonic distortion at any frequency

(d) Frequency response curve of gain in db; full-on gain, 50 db in.

(e) Signal/noise at 1 kc, 65 SPL input, full-on gain

(f) Signal/noise at 1 kc, 62½ SPL input, gain as in (c)

(g) Per cent harmonic distortion at 500, 750, 1 kc, 2 kc, and frequency of maximum distortion; 75 SPL input, gain as in (c)

(h) Per cent harmonic distortion at 500, 750, 1 kc, 2 kc; 65 SPL input, full-on gain

(i) Per cent harmonic distortion at 500, 700, and 900 c/s; 75 SPL input, at full on gain and at –10, –20, –30, –40, and –50 db.

(j) Intermodulation distortion $f$-$\Delta f$, where $f$ is progressively 500, 600, 700, 800, 900, 1 kc, 1.25 kc, 1.5 kc, 1.75 kc, and 2 kc, $\Delta f$ is 400 c/s, and $f_2$ is $f + \Delta f$. 62.5 and again 75 SPL input, gain as in (c) and again full-on.

These tests, by no means original with this report, give a fairly detailed insight into the characteristics of any aid.

It was desired to have a group of 10 aids sampling so far as possible a wide range within each electroacoustic characteristic. It is clear that for our purposes one could make a change in gain, or input level, or tone control, or battery, or type of receiver, and thus furnish in effect an entirely different set of characteristics. In choosing the final 10 aid/conditions, only seven different models were actually used: Audivox ' super 67 ', 9c receiver; Beltone 'Harmony'; Sonotones 966 and 1200; Telex; Vicon 'M-4 '; and Zenith 'Diplomat'.

However, these aids were often – even usually – used under very poor conditions, such as a 90 SPL input, or with full-on gain, etc., and no conclusions can or should be drawn comparing an aid of one company with that of another. It was desired only to set up such conditions as would give, for our purpose, the best distributions of frequency response, S/N, etc.

3. *SUBJECTS AND SENTENCE LIST PRESENTATION.*

It was desired to use two populations of normal-hearing listeners, and of partially defective patients, to ascertain whether in assessing aids in the future one could use more readily available listeners or whether it would be necessary always to perform such work in a clinical setting. Clinical patients were readily available from the E.N.T. practice of the second-named author.

Hearing loss for the 20 defectives is shown in Table I.

Each subject or patient was assigned to a cell dictated by the experimental design, and given the sentences prescribed. Listening was monaural, in an I.A.C. soundproof booth, using a Telephonics TDH-39 phone in an MX cushion, the phone fed from a Crown Model 800 tape recorder. Some later data was collected with the phone in a Willson supra-aural muff in a less well treated booth. Loudness was set, with an attenuator prior to the phone, at the most efficient (usually the most comfortable) level for each listener. Data for 10 patients had to be discarded because several of their scores for the interrupted speech condition (the most difficult of the three) were zero or nearly zero.

When the required latin square and replications had been completed, 20 normals and 20 partial defectives had each listened to the same 300 sentences through 10 aid/conditions.

* *Thanks are due to Margaret Eaton for aiding in this phase.*

TABLE I

AC AUDIOGRAMS OF DEFECTIVE PATIENTS

| Type of Loss | 250 | 500 | 1kc | 2kc | 4kc | 8kc |
|---|---|---|---|---|---|---|
| Conductive | | | | | | |
| DL | 30 | 35 | 40 | 30 | 25 | 20 |
| MB | 25 | 45 | 55 | 40 | 40 | 45 |
| EB | 50 | 45 | 40 | 55 | 55 | 45 |
| WG | 45 | 45 | 45 | 50 | 55 | 35 |
| MG | 40 | 50 | 50 | 50 | 55 | 60 |
| HM | 40 | 35 | 40 | 30 | 35 | 30 |
| Mean: | 38.3 | 42.5 | 45 | 42.5 | 43.3 | 39.2 |
| Mixed | | | | | | |
| CB | 30 | 40 | 45 | 10 | 15 | 15 |
| LL | 25 | 20 | 40 | 30 | 50 | 115 |
| JR | 35 | 30 | 30 | 0 | 20 | 20 |
| PB | 25 | 30 | 35 | 25 | 40 | 15 |
| WY | 20 | 25 | 35 | 30 | 65 | 50 |
| SL | 35 | 40 | 40 | 45 | 100 | 120 |
| Mean: | 28.3 | 30.8 | 37.5 | 23.3 | 48.3 | 55.8 |
| Perceptive | | | | | | |
| KK | 20 | 15 | 30 | 50 | 55 | 40 |
| LM | 10 | 15 | 20 | 25 | 35 | 50 |
| PG | 40 | 50 | 60 | 65 | 85 | 120 |
| MS | 15 | 15 | 60 | 65 | 60 | 60 |
| IG | 45 | 45 | 50 | 55 | 60 | 65 |
| WH | 0 | 0 | 20 | 50 | 50 | 70 |
| LK | 0 | 0 | 5 | 60 | 100 | 80 |
| OK | 20 | 15 | 20 | 60 | 75 | 90 |
| Mean: | 18.7 | 18.4 | 33.1 | 41.2 | 65. | 92.1 |

## EXPERIMENT I: RESULTS AND DISCUSSION

*1. RELIABILITY OF THE SENTENCE LISTS.*

It was noted above that the list-to-list reliability of this material is of the order of .80. Another way to assess reliability here is to compare the mean intelligibility scores of successive groups given the identical material. Table II compares the mean scores for the first 10 and the second 10 of the normal and of the defective groups. It is clear that remarkably stable scores are achieved by the methods used here, and indeed that, by massing speech material per listener as was done, it may be sufficient in this sort of work to use a panel of only 10 listeners if proper experimental design can be adhered to.

Further evidence is provided by the high rho's between the ranking of aid/conditions by the first 10 vs the second 10 listeners. For the normals the rho's for the natural, denasal-speeded, and interrupted conditions were .88, .78, and .95 in order, while for the defectives the rho's were .92, .90, and .85. Evidently a panel of 10 listeners can, in most cases, suffice to rank aid/conditions.

TABLE II

COMPARISON OF MEAN SCORE OF FIRST TEN WITH SECOND TEN LISTENERS

| DISTORTION | NORMALS | | DEFECTIVES | |
|---|---|---|---|---|
| | 1st 10 | 2nd 10 | 1st 10 | 2nd 10 |
| NATURAL | 75.2% | 75.5 | 66.0 | 63.3 |
| DENASAL-SPEEDED | 38.9 | 40.5 | 30.5 | 29.2 |
| INTERRUPTED | 18.8 | 22.4 | 10.8 | 9.9 |

*2. ANALYSIS OF VARIANCE.*

A split plot analysis of variance was performed by the third-named author on the data from the 40 listeners. The 20 defective hearing listeners had mean losses of 30, 35, and 40 db at 500, 1 kc, and 2 kc respectively and represented quite varied diagnoses.

Table III exhibits the results. There are significant differences in intelligibility for the two groups, the three speech conditions, and the 10 aid/conditions. The interaction of groups and aids ( G X H ) is significant indicating that the results on the aids vary for the two groups (although the two groups rank the aids in a similar manner within speech conditions, the poorer scores of the defectives cause this interaction with aids to become a significant one.)

The double interaction within groups of aids and conditions (H X C) is significant – the groups are giving different results on the aids from one speech condition to the other. Such a result furnishes an especial caution to later work, *not* to use *only* normal ears in hearing aid research.

Again using the analysis of variance technique, it was found that for both the normal group and the defective group, the Voice factor is very significant. The five voices used yield results that are significantly different, whether under natural, denasal-speeded, or interrupted conditions. In all cases the F test was better than 1% level of confidence.

TABLE III

MAIN PLOT ANALYSIS

| Source of Variation | Sum of Squares | df | Mean Square | F |
|---|---|---|---|---|
| Groups (g) | 31,631.59 | 1 | 31,631.59 | 10.8 |
| S's within Groups | 113,788.82 | 39 | 2,917.66 | |
| SUB-PLOT ANALYSIS | | | | |
| Hearing Aids (H) | 202,637.65 | 9 | 22,515.29 | 309.9 |
| Speech Conditions (C) | 610,243.44 | 2 | 305,121.72 | 3437.6 |
| G X H Interaction | 2,719.18 | 9 | 302.13 | 4.2 |
| G X C Interaction | 37.89 | 2 | 18.95 | --- |
| Double Inter. within G: | | | | |
| (S x C) | 6,745.97 | 76 | 88.76 | --- |
| (S x H) | 24,842.57 | 342 | 72.64 | --- |
| (H x C) | 117,609.91 | 36 | 3,266.94 | 22.4 |
| Residual | 99,825.79 | 684 | 145.94 | |
| TOTAL | 1,210,082.81 | 1199 | | |

All F's better than 1% level of confidence.

A double-classification analysis of variance was performed on the 20 defectives for each of the speech conditions, broken down by voice. In all cases F was significant, though less so for the distorted conditions. Table IV gives the three analyses. Entirely comparable results were obtained from three analyses using the 20 normal listeners.

TABLE IV

ANALYSES OF VARIANCE, 20 DEFECTIVE LISTENERS, BREAKDOWN BY VOICES

| SOURCE | Sum of Squares | df | M.S. | F. |
|---|---|---|---|---|
| Rows (Voices) | 4,485.5 (Natural) | 4 | 1,121.37 | 238.33 ** |
| | 8,733.5 (Denasal) | 4 | 2,183.37 | 42.30 ** |
| | 762.1 (Interrupted) | 4 | 190.53 | 15.78 ** |
| Columns (Aids) | 25,561.6 | 9 | 2,840.17 | 59.83 ** |
| | 8,913.58 | 9 | 990.4 | 19.29 ** |
| | 1,199.44 | 9 | 133.27 | 10.49 ** |
| Interaction (RXC) | 1,709.02 | 36 | 47.47 | |
| | 1,849.77 | 36 | 51.38 | |
| | 457.66 | 36 | 12.71 | |
| Total | 31,756.02 | 49 | | |
| | 19,496.85 | 49 | | |
| | 2,419.20 | 49 | | |

3. *RELATIVE RANKING OF AIDS.*

Fig. 1 shows articulation scores on the ordinate against aid/conditions on the abscissa. Aid/conditions are arranged in increasing rank order of difficulty for the 20 normal listeners under the natural speech condition. Note that for all three speech conditions the curves for the defective group underlie those for normals with no exceptions, but that the relative ranks assigned by the natural voice condition are only in a general way those assigned by the other two conditions. Table V gives the ranks assigned by each of the six group/conditions. The rank-order correlations between the two groups are .88, .63, and .89 for the three speech conditions in the usual order, while the correlations are .42, .51, and .41 respectively for conditions of natural vs denasal-speeded, natural vs interrupted, and denasal-speeded vs interrupted (groups collapsed). These three lower correlations point up the importance of using more than one type of speech condition in assessing hearing aids.

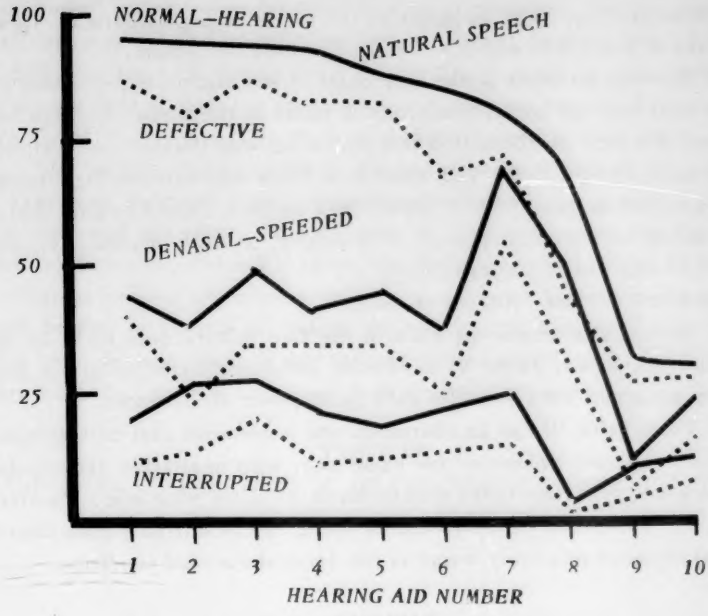


*FIG. 1: PERFORMANCE OF AIDS BY GROUP/CONDITION*

TABLE V

ARTICULATION SCORE RANK ORDERS FOR THE SIX GROUP/CONDITIONS

| Aid/Condition No. (Numbers Arbitrary) | NORMAL EARS | | | DEFECTIVE EARS | | | |
|---|---|---|---|---|---|---|---|
| | Natural | Denasal Speeded | Inter-rupted | Natural | Denasal Speeded | Inter-rupted | Overall |
| 1 | 5 | 3 | 7 | 3 | 5 | 5 | 5 |
| 2 | 3 | 4 | 3 | 1 | 3 | 1 | 1 |
| 3 | 4 | 8 | 6 | 4 | 4 | 6 | 6 |
| 4 | 10 | 9 | 8 | 10 | 9 | 8 | 9 |
| 5 | 9 | 10 | 9 | 9 | 10 | 9 | 10 |
| 6 | 1 | 6 | 5 | 2 | 2 | 7 | 3 |
| 7 | 2 | 5 | 4 | 5 | 8 | 3 | 4 |
| 8 | 6 | 7 | 2 | 7 | 7 | 4 | 7 |
| 9 | 7 | 1 | 1 | 6 | 1 | 2 | 2 |
| 10 | 8 | 2 | 10 | 8 | 6 | 10 | 8 |

A major discrepancy across conditions is seen in the aid/condition ranked seventh in Fig. 1 (Sonotone 1200). Evidently something in that aid/condition not especially apparent to the ear listening to natural speech rendered it especially efficient for the distorted conditions.

The best estimate of the rank order of intelligibility performance on these aids over all group/conditions is found in the overall average rank column. The best aid/condition is a Vicon aid with flattest tone controls, 50 db gain, 75 SPL input. The worst is a Telex with extreme high-frequency boost, full-on gain, 90 SPL input. Once again it should be said that the rank orders of instruments would be changed, probably drastically, were other settings and/or inputs used.

4. *THE ROLE OF THE INDIVIDUAL VOICE.*

Averages of scores for each of the five talkers were made up and comparisons drawn. Table VI shows the mean intelligibility in per cent for the six group/conditions for each talker, over 40 listeners.

From Table VI can be abstracted the information that both groups of listeners rank the talkers in the same way, with negligible exceptions. Furthermore, the talker ranks remain about the same when one adds distortion, except that Bob (who was able to speed up considerably more than the others) becomes relatively worse in the denasal-speeded condition.

TABLE VI
COMPARISONS OF INTELLIGIBILITY AMONG TALKERS
ACROSS GROUP/CONDITIONS
Entry: Mean Score for all 10 Aid/Conditions

| | NORMALS (20) | | | DEFECTIVES (20) | | |
|---|---|---|---|---|---|---|
| Talker | Natural | Denasal Speeded | Interrupted | Natural | Denasal Speeded | Interrupted |
| Lisa | 61.8 (5) | 37.1 (2) | 15.2 (3) | 46.6 (5) | 28.7 (2) | 5.5 (5) |
| Bob | 77.9 (3) | 28.7 (5) | 25.7 (2) | 68.3 (2) | 20.2 (5) | 14.7 (2) |
| Margie | 76.2 (4) | 34.6 (3) | 19.0 (5) | 63.8 (4) | 22.6 (3) | 8.1 (3) |
| Bill | 78.3 (2) | 33.6 (4) | 17.1 (4) | 68.2 (3) | 22.4 (4) | 7.9 (4) |
| Bernice | 82.1 (1) | 63.6 (1) | 25.6 (1) | 74.6 (1) | 55.8 (1) | 15.2 (1) |

A closer look at the percentages in Table VI shows that the voice which is poorest for normal listeners (Lisa) becomes relatively a little more difficult for defective listeners. Whereas the scores for Bernice drop off from normals to defectives by 7.5%, 7.8%, and 10.4% for the three voice conditions in usual order, the drop off for Lisa is 15.2%, 8.4%, and 9.7%.

A few significantly different mean comparisons appeared: for normal listeners, all talkers exceeded Lisa on natural condition, Bernice exceeded all others on denasal-speeded; and on interrupted, Bernice and Bob were not different, but both exceeded all others. The reasons for these differences are not hard to find: the aids simply did not pass much of Lisa's high-pitch child's voice, and Bernice was unable to speed up very much.

The further vital question is whether these voices rank the aids in the same way. To throw light on this question, scores by voice for each aid were computed and ranked for each type of distortion, using the first 10 defective listeners. Table VII shows the rho's. Only two of the 30 inter-correlations are *not* significant, and many are quite high. A conclusion would be that in general all voices are ranking the aids similarly. Lisa is the most deviant talker in this respect, which would render her type of voice more than usually necessary in this type of research.

TABLE VII
RANK-ORDER CORRELATIONS OF AID PERFORMANCE AMONG TALKERS FOR 10 DEFECTIVE LISTENERS

| | Bob | Margie | Bill | Bernice |
|---|---|---|---|---|
| Lisa | .68 Nat. | .82 | .86 | .76 |
| | .75 Den.-Sp. | .66 | .41 | .67 |
| | .47 Interr. | .36 | .56 | .54 |
| Bob | | .89 | .92 | .84 |
| | | .90 | .89 | .96 |
| | | .70 | .67 | .67 |
| Margie | | | .96 | .92 |
| | | | .89 | .85 |
| | | | .53 | .76 |
| Bill | | | | .87 |
| | | | | .87 |
| | | | | .62 |

*5- THE RELATION OF ELECTROACOUSTIC CHARACTERISTICS TO INTELLIGIBILITY.*

*a. Signal/Noise.* This variable is not covered in the most recent Amer. Standards Assoc. Standard. It was measured here simply by noting

the SPL output of the aid with and without a 1 kc signal; aid settings and input were as used in rerecording speech. The range of S/N was from 43 to 56.5 db; the rank order correlation between this feature vs overall performance (Col. 7 of Table V) was .01. Evidently once a minimum S/N is achieved (an unspecified amount but less than 43 db) any further improvement is inutile. Furthermore, the low correlation dissuades one from a fuller sampling of S/N. For example, it might otherwise have been thought useful to select perhaps a dozen frequencies at which to study S/N. Because of the technique used here of extraneous amplification to yield the most efficient listening level, one cannot make some of the usual comparisons between the overall gain-by-frequency curve and the hearing of any one patients or group of patients. Some aids badly overdriven would yield high S/N scores but very low intelligibility scores.

*b. Flatness of Frequency Response.* Steps to quantify this characteristic were as follows:

(1) A frequency-response curve was drawn for the settings and input used. Peak intensity was determined, and a horizontal line drawn 30 db down, labeled 'Overall Range'.

(2) Key frequencies (.25, .5, .75, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, and 5.5 kc/s) were each noted if they fell above the 'Overall Range' line. The median frequency of those above the line was found. The mean deviation from this line (disregarding sign) was computed (except that no deviation more than 5 db below the median (M-5 line) was considered; thus the calculation of one index of flatness was restricted to the most effective portion of the aid response.

Inasmuch as the index as calculated above could (and certainly did with aid/condition No. 3) give an erroneous picture if the frequency range were very narrow, a second index was calculated as before but disregarding the M–5 line, using instead the Overall Range line. Still a third Index was calculated, in which the area between the M–5 line and the frequency-response curve was measured in square inches with a planimeter, and diided by the frequency range in cents (a cent is 1/100 of a semitone) at the Overall Range line. This Index gives special credit to a flat, wide range.

The rho's for the three Indexes vs intelligibility are given in Table VIII. Only a few of these are significantly different from zero, and these in the negative direction.

TABLE VIII
RANK-ORDER CORRELATIONS BETWEEN INTELLIGIBILITY AND FLATNESS OF FREQUENCY-RESPONSE CURVE

| Flatness of Response Index | Overall | NORMALS Natural | NORMALS Denasal Speeded | NORMALS Inter-rupted | DEFECTIVES Natural | DEFECTIVES Denasal Speeded | DEFECTIVES Inter-rupted |
|---|---|---|---|---|---|---|---|
| No. 1 | -.57 | -.58 | -.56 | -.07 | -.56 | -.40 | -.13 |
| No. 2 | -.28 | -.60 | -.14 | +.12 | -.68 | -.33 | +.06 |
| No. 3 | -.11 | -.03 | -.66 | +.12 | -.16 | -.46 | +.16 |

The matter of flatness of response is labored here because of its high face validity. These data do not indicate an important role, although, as explained in the next section, the aid/selection was not designed to exploit this factor. Index interrelationships are seen in Table IX.

TABLE IX
INDEX OF FLATNESS OF FREQUENCY RESPONSE

| Aid/Condition | Index No. 1 (Rank) | Index No. 2 | Index No. 3 ($\times 10^{-4}$) |
|---|---|---|---|
| 1 | 6.5 (10) | 8.4 (10) | 2.31 (8) |
| 2 | 3.6 (6.5) | 6.0 (7) | 1.86 (5) |
| 3 | 2.0 (2) | 6.1 (8) | 1.37 (2) |
| 4 | 2.6 (4) | 4.4 (4) | 2.25 (6) |
| 5 | 2.2 (3) | 3.7 (2) | 1.35 (1) |
| 6 | 6.3 (9) | 7.5 (9) | 2.62 (9) |
| 7 | 4.7 (8) | 4.9 (5) | 1.51 (3) |
| 8 | 1.9 (1) | 3.9 (3) | 1.82 (4) |
| 9 | 3.6 (6.5) | 3.6 (1) | 2.30 (7) |
| 10 | 3.5 (5) | 5.9 (6) | 2.72 (10) |

No. 1: VA method (smaller mean deviations supposedly better)
No. 2: VA method disregarding M-5 line
No. 3: Total area in inches$^2$ above M-5, divided by frequency range at overall range in cents
rho's: 1 vs 2: .51; 1 vs 3: .56; 2 vs 3: .37.

*c. Frequency Range.* The range in cents was computed at the M–5 and again at the Overall Range line. However, these ranges correlated effectively zero with overall intelligibility (–.08 and –.15). But the negligible effect of frequency response in these data (and the Indexes of Flatness) was a foregone conclusion from the way these aid/conditions were selected, and does not mean that over a wide area frequency response and flatness thereof can be neglected. In order to sample extremes of harmonic distortion, gains and inputs were used approaching the saturation SPL in several aids, at which levels the frequency response on the low side flattens out, thus yielding a good score on range and flatness, but vastly degrading speech for other reasons. This selection was not thought too detrimental a compromise, since the influence of bandpass filtering and flatness on distorted speech can easily be assessed in other subexperiments.

*d. Harmonic Distortion.* This characteristic was measured in standard fashion at 500, 700, and 900 c/s. In this sample, the rho's between distortion at 500–700, 700–900, and 500–900 were .93, .77, and .67 respectively. The rho between the average distortion vs overall intelligibility was .83, which was high enough to focus attention sharply upon harmonic distortion (hereafter H.D.), although of course with a sample of only 10 one can place no great reliance on the quantitative aspect of the rho. However if one considers the data at each frequency, and for each of the six speech/listener conditions separately, a conviction grows that the rho of .83 is by no means a chance phenomenon. Against overall intelligibility, the rho's for 500, 700, and 900 c/s are of the same order of magnitude: .79, .76, and .67 respectively. Moreover, if one takes H.D. at 500 to be the most significant, the rho's between it and the six conditions are .48, .48, and .77 for the normal listeners (speech conditions in usual order), and .63, .49, and .95 for the defectives. It is not without special interest that the relation is highest, almost perfect, between H.D. at 500 and the worst of the speech/listener conditions.

*e. Intermodulation Distortion.* This characteristic was measured in a conventional way as $f_2 - f$, where $\Delta f$ was 400 c/s, and f was set in 100 c/s steps from 500 through 1 kc, and then in 250 c/s steps through 2 kc. From the curve of intermodulation distortion (hereafter I.M.) vs frequency at the input and gain settings used for speech recording, the curves being by no means smooth, the following indexes were computed:

(1) I.M. at 1 kc
(2) Maximum I.M. at any frequency
(3) Mean I.M. at 500, 750, 1 kc and 1.5 kc
(4) Mean I.M. at all 10 frequencies
(5) Integrated area under the I.M. curve from 500 through 2 kc
(6) Mean deviation of the 10 frequencies from the mean (flatness).

These data are given in Table X and show that the various ways to quantify I.M. are highly correlated, insomuch that all indexes are almost equally good, in this particular sample. If, however, one correlated them separately against overall speech intelligibility (see the last row of Table X) it is seen that those indexes are superior which best sample the total I.M. The mean I.M. over all 10 frequencies is not significantly superior to the planimeter integration, but is generally more convenient to compute and was chosen to explore the relation of I.M. to different samples of speech. The rho's of I.M. vs the three speech conditions in the usual order were .52, .27, and .49 for the normal listeners, while for the defective listenersthe rho's were somewhat higher, as expected, being .66, .55, and .53.

TABLE X

INDEXES OF INTERMODULATION DISTORTION AND THEIR RELATIONSHIP TO OVERALL SPEECH INTELLIGIBILITY

| | 1kc | Peak | Mean .5,.75,1., 1.5kc | Mean all ten | Integration under curve | Mean Deviation from mean |
|---|---|---|---|---|---|---|
| Aid/Condition | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 5.5% | 21.5% | 6.1% | 7.3% | 1.07 $in^2$ | 5.0% |
| 2 | 0.5 | 2.5 | 1.2 | 1.5 | 0.19 | 0.5 |
| 3 | 12.5 | 19 | 10.6 | 11.2 | 1.75 | 3.5 |
| 4 | 18 | 40 | 15.8 | 19.8 | 2.75 | 8.3 |
| 5 | 6.5 | 7.5 | 4.1 | 4.5 | 0.63 | 2.1 |
| 6 | 4.5 | 4.5 | 3.0 | 2.9 | 0.42 | 0.8 |
| 7 | 10.5 | 13.5 | 10.8 | 10.0 | 1.54 | 3.1 |
| 8 | 11 | 20 | 9.4 | 10.7 | 1.52 | 2.0 |
| 9 | 9 | 9 | 4.5 | 3.8 | 0.62 | 2.3 |
| 10 | 9 | 27.5 | 8.8 | 11.5 | 1.65 | 6.2 |
| rho vs overall speech intelligibility | .52 | .60 | .47 | .71 | .65 | .53 |

*f. The Relation Between Harmonic and Intermodulation Distortion.* A measure of this relation is approximated by the correlations between the best estimate of I.M. (Mn of 10 f) vs H.D. at 500, 700, and 900 c/s, and vs the H.D. of the mean of these three frequencies. The rho's were.64,.73, and .76 respectively.

## EXPERIMENT I: CONCLUSIONS

From the data of Exper. I it is possible to say that H.D., of all electro-acoustic factors studied, is most closely associated with intelligibility. Signal/Noise, Frequency Range, and Flatness of Response Curve are negligible in this sample. The relation of I.M. to speech is strong, but in this sample where the correlation between H.D. and I.M. is rather high, it is certain that much of the seeming contribution of I.M. is through its parallelism with H.D. With only 10 aid/conditions, and therefore in the absence of product-moment correlations, it is not justified to use the more powerful techniques of partial and multiple correlation to assign specific numbers to the relative contributions of H.D. and I.M. A tentative conclusion thus far would be that both are important, H.D. somewhat more so than I.M.

## EXPERIMENT II: INTRODUCTION AND PROCEDURE

Inasmuch as the rank order correlation gives only a first approximation to a relationship, it became important to extend the sample of aid/conditions in order to look more carefully into the contribution of H.D. and I.M. using the product-moment technique.

The original 10 aid/conditions were increased to 20 by passing the speech tapes through circuitry which added controlled amounts of H.D. and I.M.,* and feeding the output to the usual high quality phone at efficient loudness, with the addition of an attenuator and a high fidelity amplifier. The amounts of H.D. were varied from 4 through 55, in more regular increments than in Exper. I. I.M. as measured at 1 kc only (Index 1, Table X), varied from 1.4 through 15%.

Twenty different defective listeners (Mean hearing losses at the octaves 250 – 8 kc: 36, 34, 35, 37, 45, 45) heard five sentences through each aid under natural, and five under denasal-speeded conditions.** A design was arranged so that no patient heard the same sentence twice. In general, the procedure included counterbalancing as in Exper. I.

## EXPERIMENT II: RESULTS AND DISCUSSION

Table XI gives the intelligibility scores, and the percentage of H.D. and I.M. for each aid/condition. The product-moment r's are given at the bottom, for the speech conditions separately. The significant contribution of H.D. to intelligibility as found in Exper. I is corroborated, as well as the somewhat weaker contribution of I.M. (Had another index of I.M. been used, these figures may have been somewhat different.)

* *Thanks are due Mr. Philip Douglas for this phase.*

** *Thanks are due Mr. Jerome Murphy for assistance.*

TABLE XI

% OF NONLINEAR DISTORTIONS AND INTELLIGIBILITY SCORES

(N: 20 DEFECTIVE LISTENERS)

| Aid/ Condition | Mean Intelligibility Natural | Denasal | % Harmonic Distortion | % Intermodulation Distortion |
|---|---|---|---|---|
| 1 | 82.1% | 38.0% | 4.75 | 1.5 |
| 2 | 85.2 | 39.9 | 5.0 | 1.6 |
| 3 | 78.9 | 60.9 | 7 | 5.2 |
| 4 | 84.8 | 39.6 | 9 | 1.7 |
| 5 | 81.3 | 37.4 | 12 | 2.0 |
| 6 | 90.6 | 35.6 | 14 | 1.4 |
| 7 | 90.2 | 30.9 | 15 | 3.1 |
| 8 | 87.0 | 36.9 | 16 | 1.6 |
| 9 | 88.6 | 33.2 | 18 | 1.9 |
| 10 | 86.6 | 33.1 | 20 | 2.4 |
| 11 | 64.6 | 53.5 | 22 | 10.2 |
| 12 | 87.4 | 30.6 | 24 | 13.0 |
| 13 | 72.5 | 30.7 | 26 | 9.2 |
| 14 | 75.3 | 27.6 | 28 | 9.4 |
| 15 | 84.7 | 27.0 | 30 | 13.5 |
| 16 | 84.9 | 34.6 | 33 | 13.5 |
| 17 | 27.5 | 6.2 | 35 | 11.0 |
| 18 | 86.4 | 37.5 | 40 | 14.0 |
| 19 | 28.1 | 17.4 | 55 | 15.0 |
| 20 | 47.7 | 40.7 | 55 | 10.0 |

Natural Speech; Denasal Speeded

| | H.D. | I.D. |
|---|---|---|
| Intell: | r: .67; .45 | r: .49; .33 |
| H.D. | | r: .80 |

The strong relationship (r of .80) between H.D. and I.M. also corroborates the rho's of the same order of magnitude in Exper. I. In fact, this relationship is so strong that in Exper. II the Multiple $\overline{R}$ for H.D. is not significantly increased by adding I.M. to the equation, for either speech condition.

## EXPERIMENT II: CONCLUSIONS

Expanding the aid/conditions to 20 by the quick procedure of this experiment allows the use of the more desirable product-moment r, but the conclusions of Exper. I are unaltered, that in this sort of circuitry H.D. is the single most important electroacoustic characteristic measured, with I. M. somewhat less so. The absolute size of the r's would indicate that H.D.alone can account for 20 – 45% of the total variance in scores. This conclusion it must be remembered comes from 20 aid/conditions, it is true, but from only seven actually different units and may be tempered later on.

## EXPERIMENT III: INTRODUCTION AND PROCEDURE

The above conclusions seemed important enough to warrant cross-validation and extension on a completely different set of hearing aids, especially since it could be expected that the former group of seven aids was too restricted in the distribution of electroacoustic variables tested. In this third sampling, 19 separate aid-receiver combinations were used;a nineteenth was used with two 'tone' settings.

Furthermore, in order to render conditions somewhat more comparable to real life, and to avoid grossly distorting certain frequency-response curves, an input of 75 SPL was used for all speech rerecording.It will be recalled that previously inputs up to 90 SPL had been used.

Since it was especially desired to check the relation between H.D. vs intelligibility, aid/conditions were picked over with 75 SPL input at 500, 700, and 900 c/s until a nearly square distribution of H.D. ranging up to about 40% in about 2% steps was achieved. Without delay when its gain had been set, speech in all three modes was led to the aid at 75 SPL and the output rerecorded in the usual fashion.

At a later date, the conditions for each aid were reconstituted and the aid carefully examined for I.M. as in Exper. I but with $\Delta f$ of both 150 and 400 c/s. Information on quadratic distortion (the difference tone) and cubic distortion ($f - \Delta f$, plus $f + 2\Delta f$) were obtained at 20 frequencies.

Twenty partially defective patients were given five sentences in each mode by each of the 20 aids, all relevant counterbalancing used.

## EXPERIMENT III: RESULTS AND DISCUSSION

The electroacoustic data, and speech scores, are given in Table XII.

The r's among the three speech tests range from .80 to .88; between H.D. and the speech modes in the usual order are .57, .71, .66 (.70 for total of all modes). Thus, H.D. again establishes as an important determiner for all types of speech. On the other hand, although I.M. was more than adequately sampled (total cubic for $\Delta f$ of 150 vs total cubic for $\Delta f$ of 400

was .65), its relation to intelligibility was not significant (the range of six r's of cubic I.M. vs modes was .08 to .25 of quadratic I.M. −.13 to −.1).

These r's should be interpreted in the light of their non-normal distributions: H.D. was a square distribution by design, whereas I.M. by the best index in these data (total cubic where Δf is 400) was nearly normally distributed but had one greatly atypical value. Probably the relation expressed here for intelligibility is a bit too high; on the other hand, that for I.M. is probably a bit too low. But there can be no doubt as to the considerably greater contribution of H.D. than of I.M. to the variance in these data.

The non-normality of these distributions would in any case dissuade one from entering the r's in higher-order correlation formulae, but also it is clear from the relative sizes of the r's that nothing would be gained by adding I.M. to H.D. for prediction purposes.

TABLE XII

RAW DATA FROM EXPERIMENT III: INTELLIGIBILITY AND ELECTROACOUSTIC CHARACTERISTICS

| Aid No. | Column A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | 25.5 | 68.0 | 86.2 | 25.3 | 4.8 | 5.1 | 8.0 | 39.5 |
| 2 | 35.9 | 81.7 | 92.5 | 1.3 | 12.0 | 9.6 | 22.5 | 40.5 |
| 3 | 23.0 | 65.6 | 89.1 | 4.8 | 6.0 | 4.6 | 5.3 | 34.7 |
| 4 | 23.9 | 61.3 | 84.2 | 3.2 | 1.5 | 1.2 | 2.0 | 31.8 |
| 5 | 17.9 | 69.1 | 75.3 | 2.3 | 1.3 | 1.5 | 3.6 | 33.1 |
| 6 | 14.1 | 57.5 | 80.6 | 17.1 | 20.7 | 20.8 | 20.0 | 43.2 |
| 7 | 13.4 | 64.6 | 82.4 | 11.5 | 11.3 | 13.6 | 10.0 | 44.4 |
| 8 | 30.0 | 79.7 | 92.0 | 4.7 | 6.6 | 5.4 | 25.0 | 41.1 |
| 9 | 38.2 | 86.7 | 92.1 | 25.0 | 11.9 | 14.8 | 41.0 | 49.0 |
| 10 | 48.8 | 90.6 | 97.5 | 9.0 | 19.5 | 8.6 | 30.0 | 43.7 |
| 11 | 23.5 | 81.3 | 92.3 | 10.0 | 17.9 | 7.0 | 39.0 | 45.7 |
| 12 | 24.6 | 71.2 | 89.0 | 61.3 | 64.6 | 19.9 | 34.0 | 36.5 |
| 13 | 21.5 | 68.0 | 83.5 | 3.8 | 5.0 | 5.5 | 6.0 | 36.7 |
| 14 | 17.2 | 67.1 | 81.5 | 6.3 | 6.3 | 5.0 | 13.5 | 29.4 |
| 15 | 19.4 | 59.2 | 83.0 | 30.0 | 7.0 | 6.4 | 18.0 | 36.6 |
| 16 | 30.9 | 74.2 | 93.6 | 5.1 | 4.1 | 2.1 | 23.0 | 30.3 |
| 17 | 24.0 | 67.1 | 81.5 | 22.4 | 3.7 | 8.6 | 15.0 | 36.0 |
| 18 | 19.5 | 66.7 | 85.0 | 6.4 | 20.2 | 22.2 | 17.0 | 51.8 |
| 19 | 28.2 | 73.1 | 83.9 | 28.7 | 10.2 | 10.0 | 27.5 | 44.8 |
| 20 | 41.3 | 88.4 | 94.3 | 4.1 | 16.5 | 22.3 | 31.0 | 36.2 |

A–C: Mean Error Scores in Per Cent Correct for Natural, Denasal–Speeded, and Interrupted Speech

D–F: Intermodulation Indexes. D:: Δf (Mn of 10 f); E: f−Δf + (f +2Δf) (Mn of 10 f), where Δf =400 c/s; F: As (E) but Δf =150 c/s

G: Harmonic Distortion (Mn of 500, 700, 900 c/s

H: Frequency Range in Cents x 100 (1200 cents in one octave)

The data from Exper. III on I.M. confirm the earlier studies only in the greater importance of H.D. Both Expers. I and II assigned a significant, though minor, role to I.M. but Exper. III, with a better statistic or selection of aid/conditions, does not confirm the significance of I.M.

The r between H.D. vs quadratic I.M. distortion (Col. D, Table XII) is .37; between H.D. vs cubic I.M. (Col. E) is .53)

A look at Table 12 will show the nature of the mild relation between H.D. and intelligibility. It would seem that, other things being equal, H.D. does not appreciably degrade speech until it exceeds 20%.

Other electroacoustic characteristics tested provide no further gain in prediction of intelligibility. S/N, measured as in Exper. I, correlated -.07 with total error score. The correlation for S/N vs H.D. was .11, for S/N vs Frequency Range was -09.

Another attempt was made in Exper. III to relate frequency range, and flatness of frequency-response to intelligibility. It will be recalled that in Exper. I flatness was markedly affected in many cases but in an irrelevant manner by an overloaded input. In Exper. III this unwanted feature was eliminated by using an input of 75 SPL for all aids. Nevertheless here, too, neither flatness Index No. 1 nor No. 2 (as described in Table IX and accompanying test) was a significant contributor. A significant, though slight, effect of frequency range (computed from a +5db slope/octave at the "overall" range line) was found (r=.25). This is higher than had been found in Exper. I.

A correlation of .50 between H.D. and frequency range merely reflects the fact that the higher cut-offs allow more higher-order harmonic to pass.

An attempt was made to relate intelligibility to the auditory area between the frequency-response curve and the noise level of the instrument in a way which could not with meaning be done in Exper. I. The auditory area made available by the aid was plotted in the usual fashion on semilog paper (5 in/cycle; 10 db/in) and measured with planimeter to the nearest .01 sq. in. In addition, the area was measured above the line 30db down from the peak (see the concept of the useful "overall range" in Exper. I). Neither of these indexes correlated significantly with intelligibility.

It can be taken for granted that the recorded tapes and the playback system transmitted the frequency and dynamic ranges, represented by the auditory area, to the subject's ear without distortion.

The low (though in fact significant) correlation between the useful area passed by the aid vs intelligibility is surely because of the restricted sample. As the frequency range is narrowed, or the dynamic range decreased, a point must come at which intelligibility disappears. In this sample of now commercially available aids, it must be that the minimum limits for intelligibility have been exceeded in all or nearly all models. The modern aid has evidently evolved to the point of diminishing returns both in frequency range and in intensity range.

## EXPERIMENT III: CONCLUSIONS

The data of Exper. III are interpreted as follows:

a. H.D. again emerges as contributing about half of total variance. It must, however, exceed 20% to degrade speech appreciably.

b. I.M. is reduced in relative importance; the higher contribution to intelligibility found earlier in Expers. I and II must have risen largely from its relation to H.D.

c. Neither cubic nor quadratic I.M. is a factor in intelligibility

d. Frequency range is significantly but slightly associated with intelligibility; most of the aids in this sample satisfy a minimum range requirement unspecified here except that it must be less than 2½ octaves.

e. Frequency-response in the typical modern aid is sufficiently flat for good speech communications.

f. No further gain in S/N over 25 db will as such increase intelligibility.

g. The auditory area passed by the aid is a moderate predictor of intelligibility; but following the reasoning of (d) and (f) above, it would seem that the modern aid has a safety factor of some appreciable magnitude over and above the area needed as a minimum.

## GENERAL DISCUSSION

The present data indicate that real differences in speech–handling capacities do exist among various hearing aids now commercially available. Most of them exceed minimum requirements for S/N, frequency range, flatness of frequency response, and perhaps intermodulation distortion but critical differences in other electroacoustic characteristics exist. Some previous thought that evaluations cannot reliably be made in the usual clinical setting may rest upon current use of too-brief testing, and/or the usual omission of stressed speech to make finer differentiations.

For the assessment of differences in everyday use among low-fi communication circuits, a panel of at least ten listeners may be given a minimum test consisting of at least three samples of speech condition, at least five different voices, and using connected discourse involving at least 25 key words per condition. Such a test will have a cross-group reliability of about .90. For circuitry designed for normal-hearing listeners, such a panel should be convened; for hearing aids, partial defectives should be used.

For the reliable assessment of the increased intelligibility which a particular aid may provide for a patient, the same minimum test should be

completed. It would be inadvisable to base an important decision on a test involving less effort. Certainly the usual aided–unaided SRT using one undistorted voice and one or two spondee lists is insufficient.

The technique of storing speech material after having been passed through a hearing aid is a great time-saver and greatly facilitates standardizing acoustic conditions from one subject to the next. It should definitely be used in most work of this sort.

All three experiments show harmonic distortion, alone of all the several electroacoustic characteristics studied, to affect intelligibility in any really significant amount.

The role of I.M. is somewhat confusing, since it too correlates significantly with intelligibility. However, its contribution is held to be negligible as a second factor in these data; because of its high correlation with H.D. its addition in a multiple correlation formula does not yield a better predicition than does H.D. alone.

The writers are not qualified to give an engineering discussion of the relation between H.D. and I.M., nor of the relations among the several types of I.M., but it is perfectly obvious that as breakdowns in input-output linearity H.D. and I.M. must be very similar both as to cause and effect. Whether a single frequency at the input gives rise to a second and higher order harmonics, or whether two frequencies at the input give rise to a series of difference and summation tones, the effect is in each case to impart at least a modicum of cue masking, and even misleading information, to the ear. A circuit which produces controlled amounts of one type of distortion and none of the other type has not been used in hearing aid research. In fact, the chief distinction between the two lies simply in how one chooses to measure nonlinear distortion in general. The relative effect of H.D. and I.M. on speech intelligibility, then, will lie in relations among the spectrum and levels of specific speech signals, and the particular frequency or frequencies at which H.D. or I.M. are especially strong.

The absolute size of the r's would indicate that H.D. can account for about 50% of the total variance in intelligibility scores through these aids. Other untapped electroacoustic characteristics, such as transient distortion*, must be explored to account for such of the variance remainder as is not attributable to chance or unreliability of the intelligibility scores.

The fourth-named author has suggested a possible reason for the rather surprising differences in the contribution to intelligibility of H.D. and I.M. Both have the effect of adding line spectra to the signal, but in the

* *In spite of our best efforts, assisted by Mr. Philip Douglas, transient distortion could not be quantified in a meaningful way without the availability of a good square-wave-following transducer.*

case of H.D. these are likely to be at just the worst possible frequencies. In all phonemes the formants are related to the fundamental in a fashion which very nearly simulates the harmonic relationship. Harmonic distortion products of the fundamental thus will overlie and tend to mask or otherwise obscure the information contained in the formant structure of the phoneme. The products of I.M., on the other hand, will usually lie in other regions altogether and, because of the critical bandpass action of the hearing mechanism, these I.M. products can be rendered irrelevant.

## SUMMARY AND CONCLUSION

Three experiments were performed with hearing aids as examples of low-fi communication circuitry. Speech intelligibility was related to Signal/Noise, frequency range, flatness of frequency-response curve, harmonic and intermodulation distortion.

A minimum test for intergroup reliability of about .90 was determined to be a sample of connected colloquial discourse, using at least five talkers and three speech conditions (natural, denasal-speeded, and interrupted were used here). A total of at least 25 key words was used for each speech condition. Such a test might well be considered a minimum either for assessment of a circuit across groups or for individual hearing aid fitting.

Practically all hearing aids currently on the market meet minimum requirements of S/N, frequency range, and flatness of frequency response. Frequency range yielded an r of .25 with intelligibility. Distortion products were definitely implicated. Correlations of the order of .70 were commonly obtained between harmonic distortion and error scores. Intermodulation also yielded significant though lower r's with intelligibility, but it is felt that its contribution was by way of its strong relationship to harmonic distortion. To explain the greater effect of harmonic distortion an hypothesis was advanced assuming a masking effect of harmonic distortion products of the fundamental upon the frequency regions of the phonemes.

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